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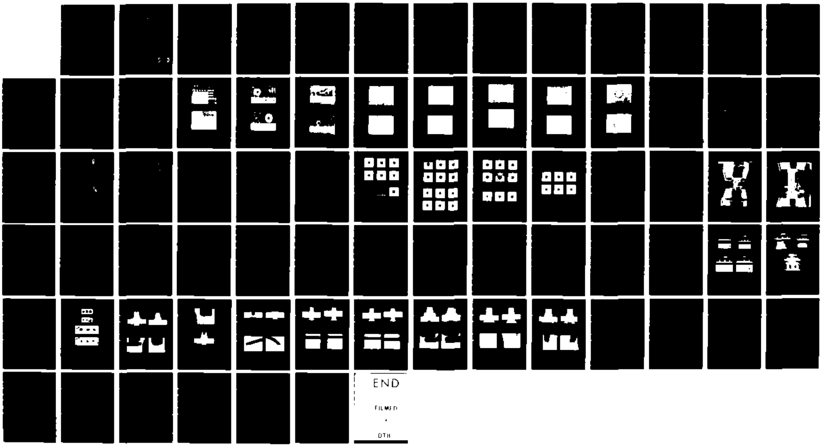

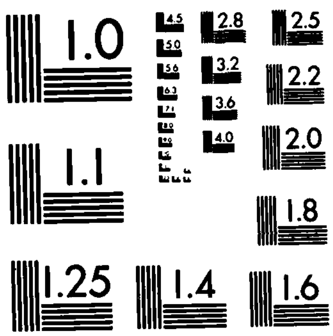

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INVESTIGATION OF HOLE PREPARATION AND FASTENER INSTALLATION FOR GRAPHITE/EPOXY LAMINATES

McDonnell Aircraft Company
McDonnell Douglas Corporation
P.O. Box 516
St. Louis, Missouri 63166

E.F. Condon

August 1980

Technical Report N00019-79-C-0293
Final Report for Period 1 November 1979 - 29 August 1980

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Department of the Navy
Naval Air Systems Command
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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The object of this program was to determine the effect of various hole anomalies on the static and fatigue strength of graphite/epoxy laminate and to determine the effects of installing production fasteners in graphite/epoxy laminates. Static tests at room temperature and 250°F with dry and wet (1% moisture) specimens indicated that only interply delaminations caused a significant strength reduction. Fastener installation tests showed blind bolts and solid rivets caused installation damage and that blind rivets, threaded rivet pins, and pull type lock bolts did not show installation damage.

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FOREWORD

This final report covers work performed under Contract No. N00019-79-C-0293 from November 1979 to August 1980. Work was performed under the direction of the Material and Process Development Department of the McDonnell Aircraft Company, McDonnell Douglas Corporation, St. Louis, Missouri. The program was administered under the direction of Naval Air Systems Command by Mr. Max Stander.

The program was managed by Mr. H. C. Turner with Mr. E. F. Condon as the Principal Investigator.

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LIST OF ILLUSTRATIONS (Continued)

1.0 INTRODUCTION

This is the final technical report for this contract. It covers work accomplished from 1 November 1979 to 29 August 1980.

The use of graphite/epoxy (Gr/Ep) components on fighter aircraft produced by McDonnell Aircraft Company (MCAIR) has greatly increased since 1975. Early application of Gr/Ep required the drilling of approximately 100 holes in laminate details during aircraft assembly. Recent fighter aircraft such as the F-18 and AV-8B use a much greater amount of Gr/Ep and therefore require the use of thousands of fasteners and fastener holes. Methods have been developed to produce fastener holes efficiently and to strict quality requirements.

However, drilling anomalies such as excessive heat, roughened surfaces, interply delamination, and splintering (surface delamination) still occur in holes. Repairs to salvage the details can be costly and difficult. Therefore, the primary objective of this program was to evaluate the effect of anomalies on the static and fatigue strength of Gr/Ep laminates to determine whether hole quality requirements can be relaxed to reduce repair costs and scrap rates.

At the present time, fastener selection for use with Gr/Ep is limited. Costly countersunk bolts and Hi Lok fasteners are the predominant ones used. It would be desirable to also use less costly solid rivets, blind rivets, lock bolts, and blind bolts in production systems. Therefore, an additional objective of this program was to evaluate the installation effects of these fasteners on holes in Gr/Ep laminates.

2.0 SUMMARY

The plan used during this program is shown in Figure 1. Production anomalies simulated and evaluated in this program are excessive heat, rough hole surfaces, interply delaminations, and splintering (surface delamination). Drilling techniques were developed to consistently produce each of these anomalies.

The laminate used in this program was 20 plies thick with a layup orientation of $(45, 0, -45, 0, 45, 90, -45, 0, 45, -45)_s$, representing typical wing skin laminate used at MCAIR. Unidirectional AS/3501-6 prepreg with a nominal resin content of 35% and a nominal cured ply thickness of 0.0104 inches was used.

Static and fatigue test specimens were fabricated representing each of six anomalous hole conditions as well as holes of acceptable quality (baseline) and tested per Figure 2. All holes were initially filled with 1/4 inch diameter, 100° countersunk, Hi-Torque head stainless steel bolts. Specimens were radiographically and ultrasonically inspected prior to testing.

The static tests indicate that none of the anomalies tested significantly affected tensile strengths for unloaded hole specimens, but compressive strengths for unloaded hole specimens were affected by interply delaminations. Loaded hole results indicate that the dry and wet tensile strengths were not appreciably affected by the hole anomalies.

Fatigue tests of dry specimens indicate that interply delaminations again have the most significant effect. Rough hole surfaces also decreased dry fatigue life, but to a lesser extent.

Fastener installation tests were performed on specimens fabricated from the same ply layup type laminate used for evaluating hole anomaly effects. Fasteners installed included threaded rivet pins, solid rivets, blind rivets, flush head Hi-Torque bolts, flush head blind bolts, and pull type lock bolts. Ultrasonic and radiographic inspections were made of the installation specimens before the fasteners were installed and ultrasonic inspections were made afterward to determine if the fasteners had damaged the laminate. Typical specimens were then sectioned through the fasteners and holes to evaluate installation effects on the holes.

Fastener installation tests showed that rivet pins, blind rivets, and pull type lock bolts did not cause damage to Gr/Ep. However, solid rivets and blind bolts did cause significant damage.

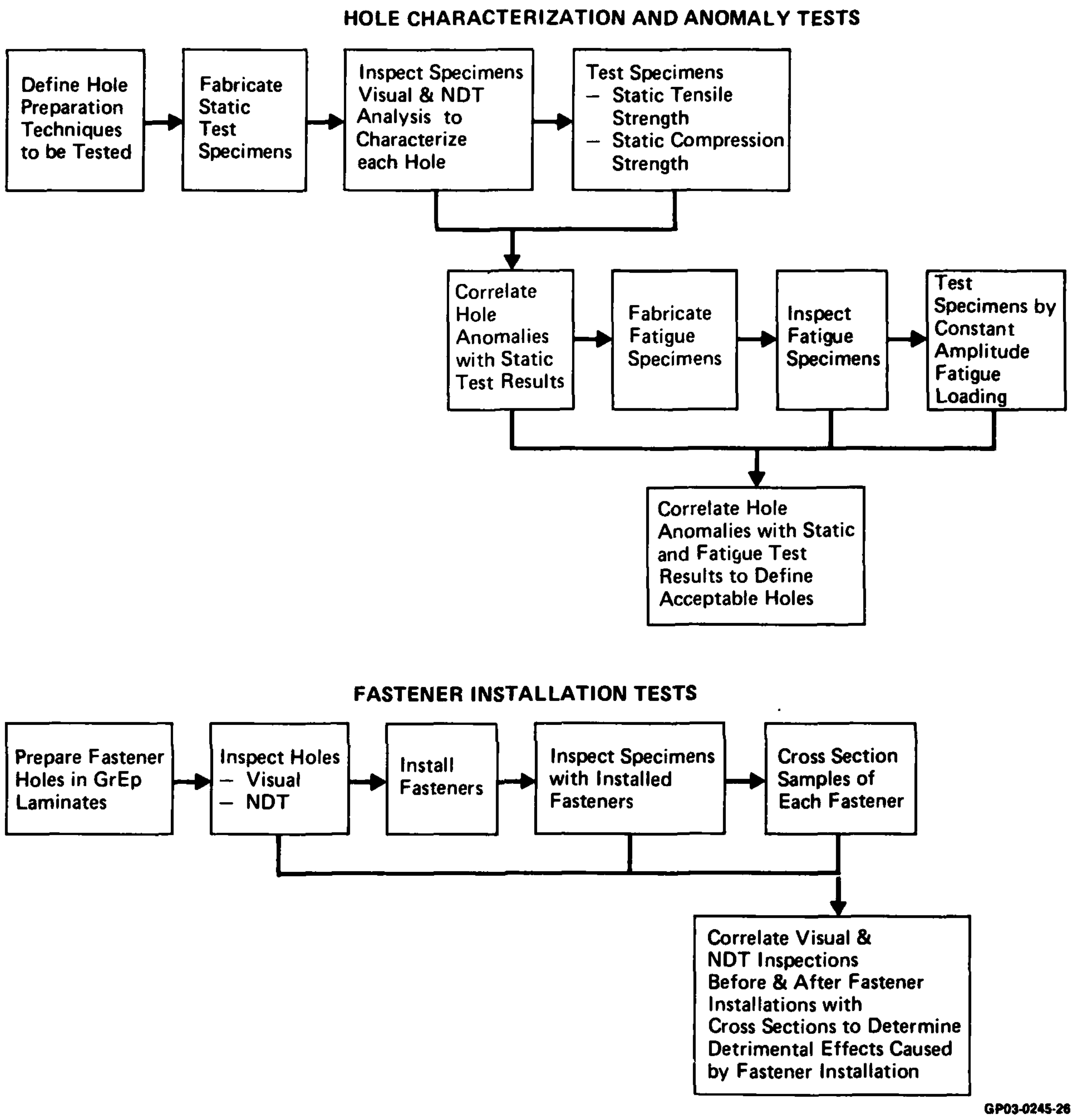

Figure 1. Program Plan

Hole Condition	Quantity of Specimens Per Test Configuration					
	Static Tests					Fatigue Test R = –1
	Unloaded Hole (Tension)	Unloaded Hole (Compression)		Loaded Hole (Tension)		Unloaded Hole
		Dry	Wet ⚠1	Dry	Wet	Dry
(A) Baseline • Heat Below 275°F • No Delaminations/Splintering • Surface Finish Smoother than 125 RHR	3	3	3	3	3	3
(B) Excessive Heat	3	3	3	3	3	3
(C) Delaminations: Some Splintering	3	3		3		
(D) Delaminations: Much Splintering	3	3		3		
(E) Delaminations: Interply Delaminations	3	3	3	3	3	3
(F) Surface Finish: Rougher than 125 RHR	3	3		3		
(G) Surface Finish: Rougher than 250 RHR	3	3	3	3	3	3

⚠1 Specimens with 1% water content, tested at 250°F

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Figure 2. Test Matrix

3.0 RESULTS

The following sections describe the fabrication and inspection of the test specimens and the results of all tests performed.

3.1 TEST SPECIMEN FABRICATION - Two 36 inch x 48 inch, 20-ply laminates were fabricated using MCAIR standard production practice. Layup of the laminate was: $(45, 0, -45, 0, 45, 90, -45, 0, 45, -45)_S$, i.e. 30% of the fibers were oriented in the 0° direction, 60% in the +45° or -45° direction and 10% in the 90° direction. The 0° orientation was parallel to the 36 inch dimension of the laminate panels. Unidirectional AS/3501-6 prepreg was used; the prepreg had a nominal 35% resin content and cured to a nominal thickness of 0.0104 inch per ply.

These panels were acceptable when radiographically and ultrasonically inspected; however, a visual inspection of some areas showed some surface fiber waviness. It was determined that some wrinkled and puckered prepreg tape, which normally is cut out during layup, had been used in fabricating the first panel. It was decided that since compression tests are part of this program, new panels would be fabricated and these first panels would be used for drilling parameter development. The new panels also were acceptable radiographically and ultrasonically and exhibited no fiber waviness.

Interlaminar shear tests of 0° process control specimens cured with the laminate were performed at room temperature and 250°F. Results indicated acceptable average values of 18,500 psi at 75°F and 13,600 psi at 250°F.

The drilling parameters developed to consistently produce the individual anomalies in the 20-ply laminate are shown in Figure 3. Anomaly "E" required an intermediate operation in which a load was applied with a nondrilling mandrel to produce interply delamination within a predictable area of the laminate, after which the drilling was completed. Figures 3, 4 and 5 illustrate the drilling and delamination operation details. The initial delamination and subsequent deflection were determined by load deflection curves such as those shown in Figure 5. Figures 6 through 21 are photographs of the various anomalies produced.

3.2 NONDESTRUCTIVE EVALUATION - The holes and the various anomalies were inspected by both ultrasonic and radiographic techniques.

Ultrasonic inspection techniques possess the resolution required to identify and describe the flaw, determine its depth, and map its extent. They include contact-coupled pulse-echo, pitch-catch, and through-transmission, and immersion or squirter-coupled reflector-plate, through-transmission, or pulse-echo.

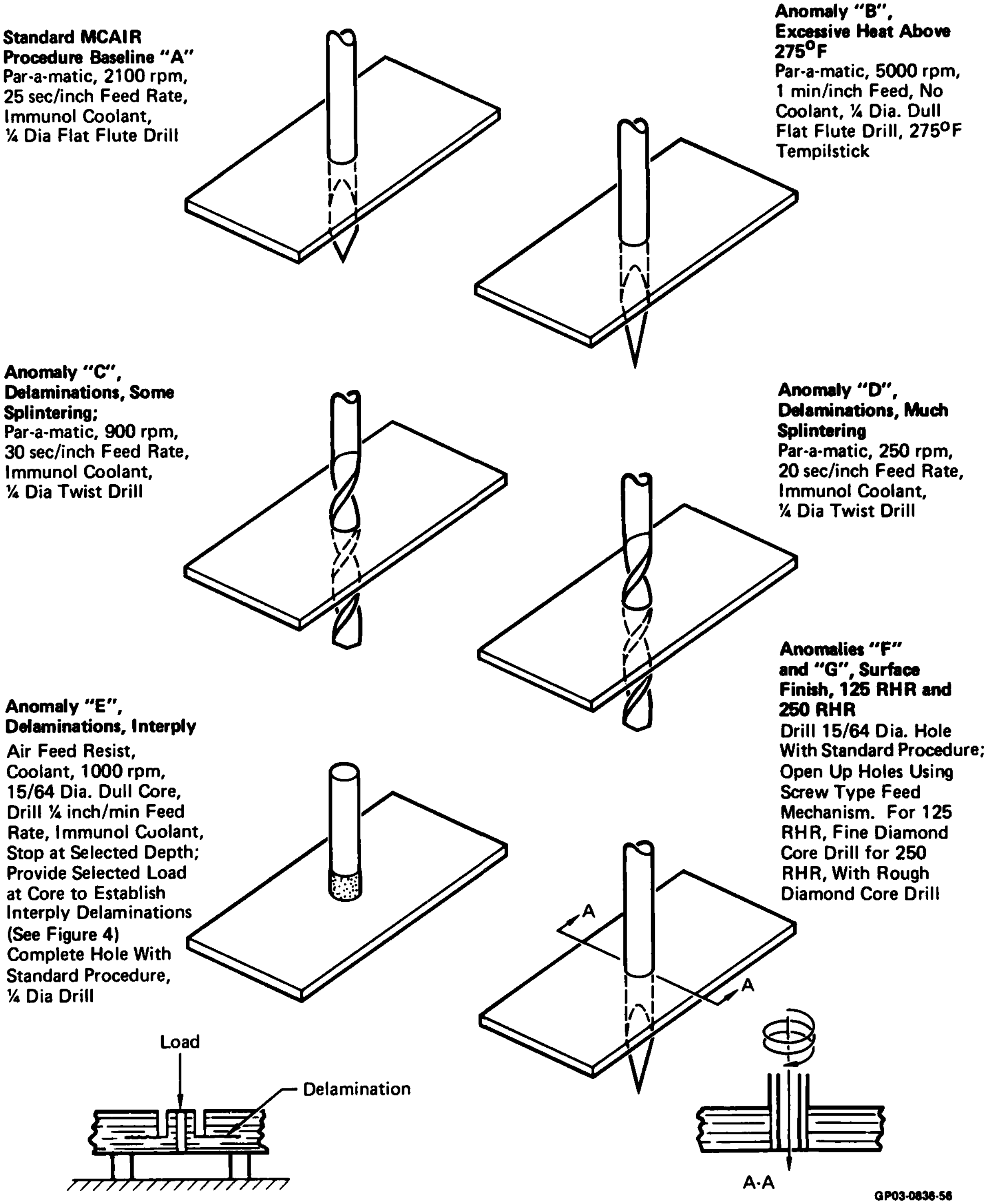
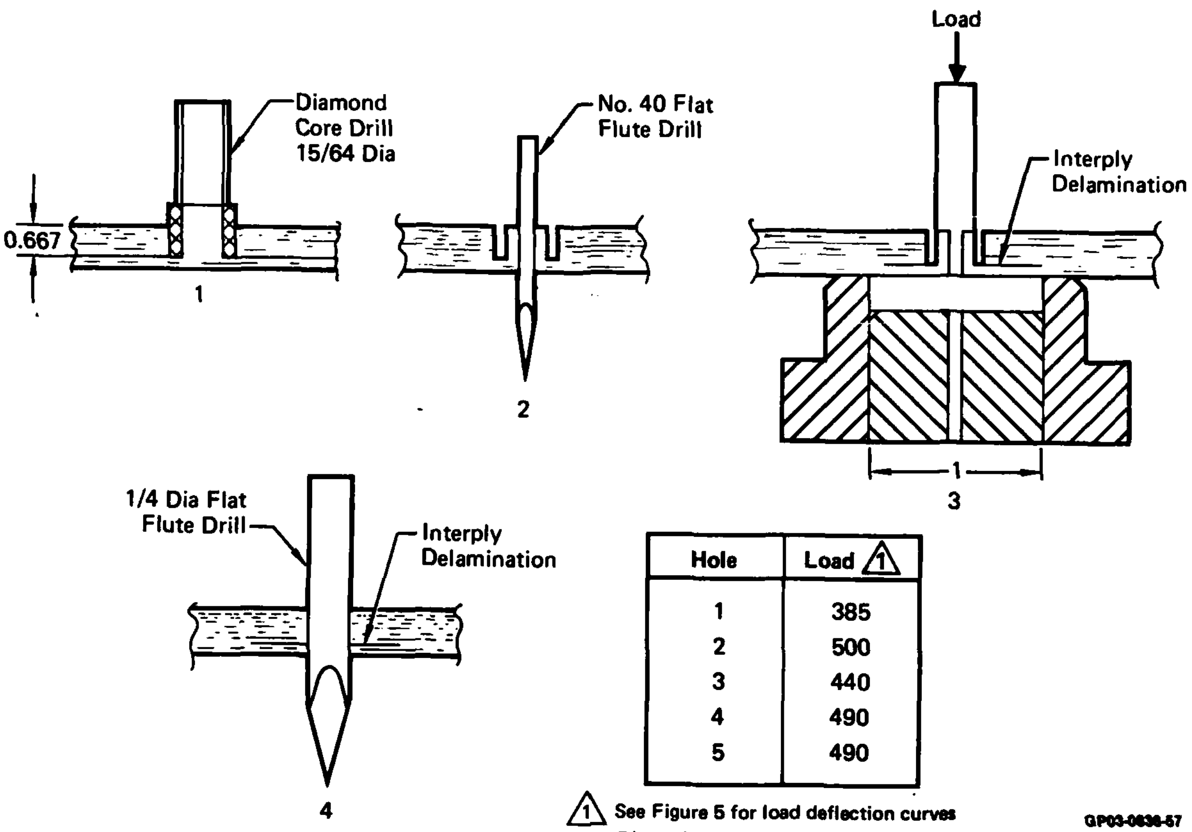


Figure 3. Drilling Parameters



Hole	Load ⚠1
1	385
2	500
3	440
4	490
5	490

⚠1 See Figure 5 for load deflection curves
Dimensions in inches

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Figure 4. Anomaly-E, Parameters, Interply Delaminations

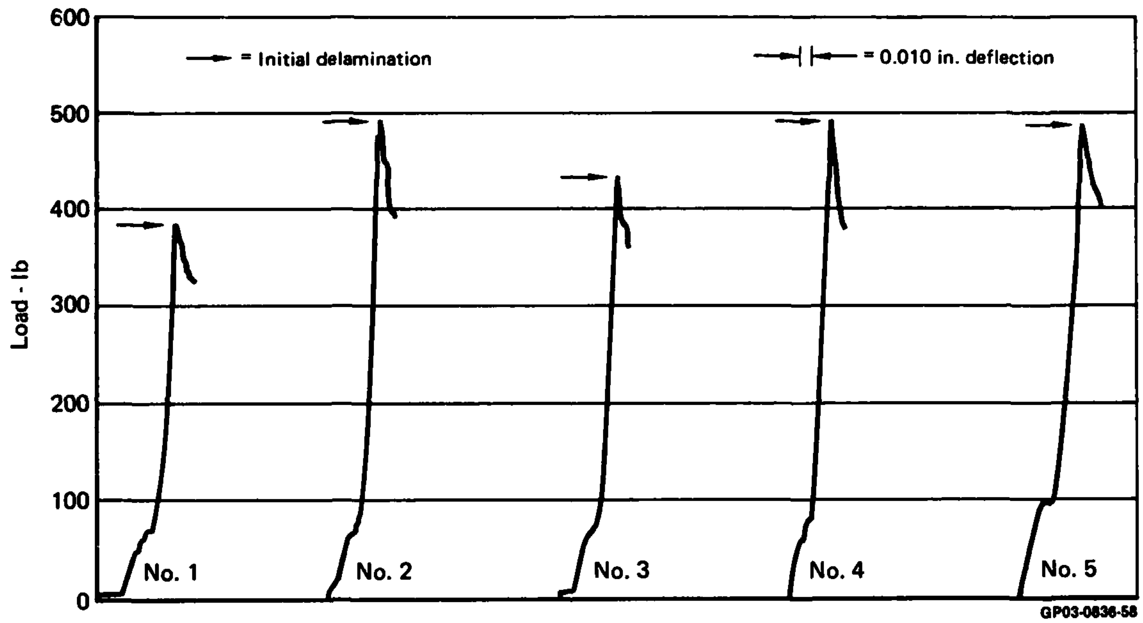

Figure 5. Anomaly-E, Delaminations Interply, Load Deflection Curves

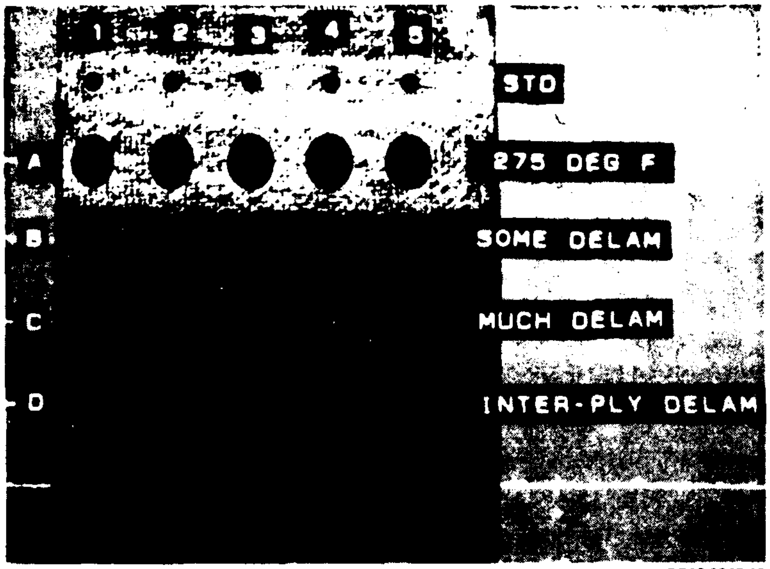

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Figure 6. Test Panel Drill Entrance Side

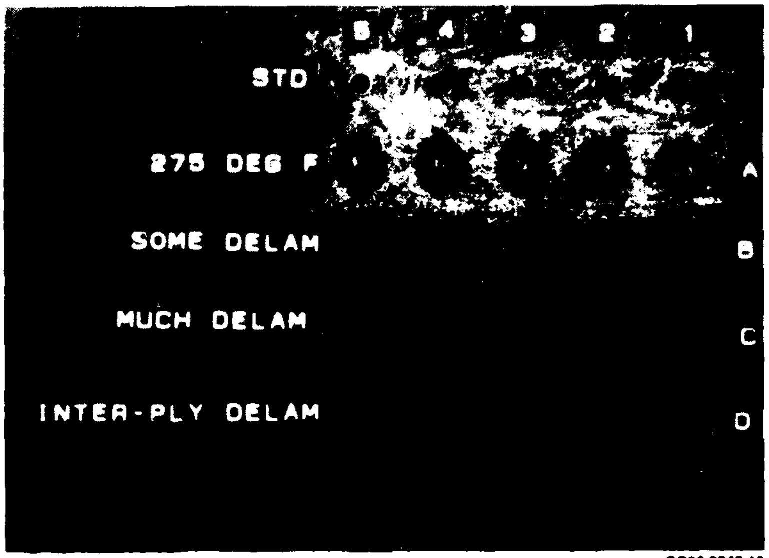

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Figure 7. Test Panel Drill Exit Side

Figure 8. Standard Hole and 275°F Tempilstick Entrance Side (2X)

Figure 9. Standard Hole and 275°F Tempilstick Exit Side (2X)

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Figure 10. Standard Hole and 550° Tempilstick Entrance Side (2X)

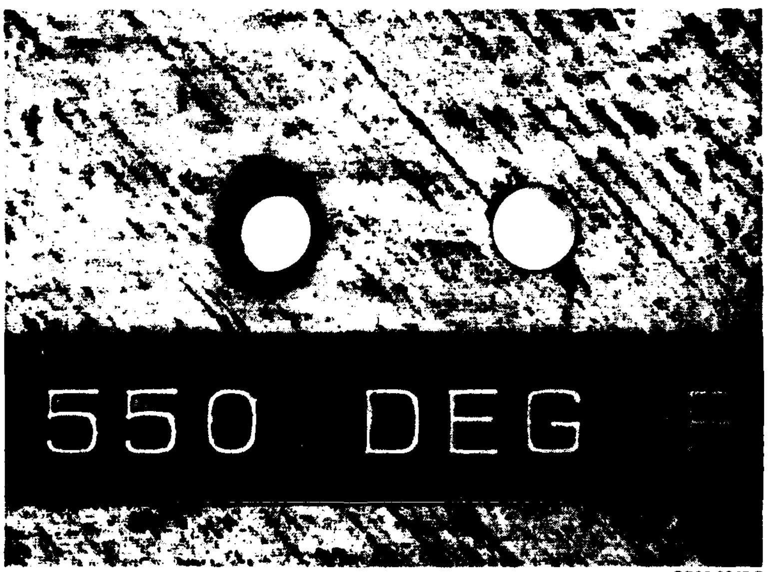

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Figure 11. Standard Hole and 550°F Tempilstick Exit Side (2X)

Figure 12. Standard Method Entrance Side (10X)

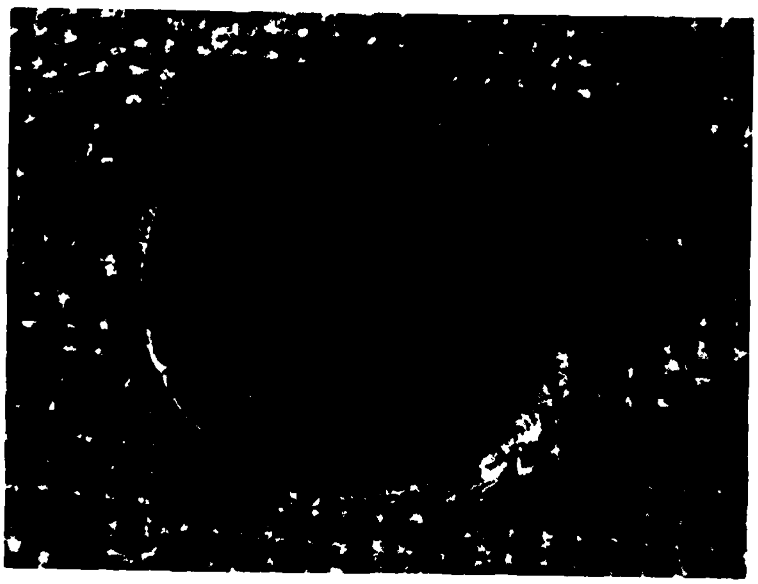

Figure 13. Standard Method Exit Side (10X)

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Figure 14. Anomaly-B, Excessive Heat Above 275°F Entrance Side (10X)

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Figure 15. Anomaly-B, Excessive Heat Above 275°F Exit Side (10X)

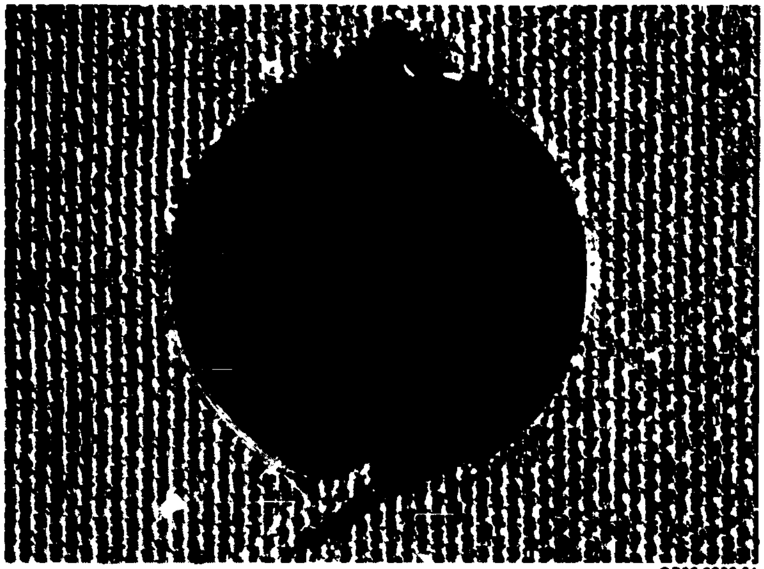

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Figure 16. Anomaly-C, Delaminations, Some Splintering Entrance Side (10X)

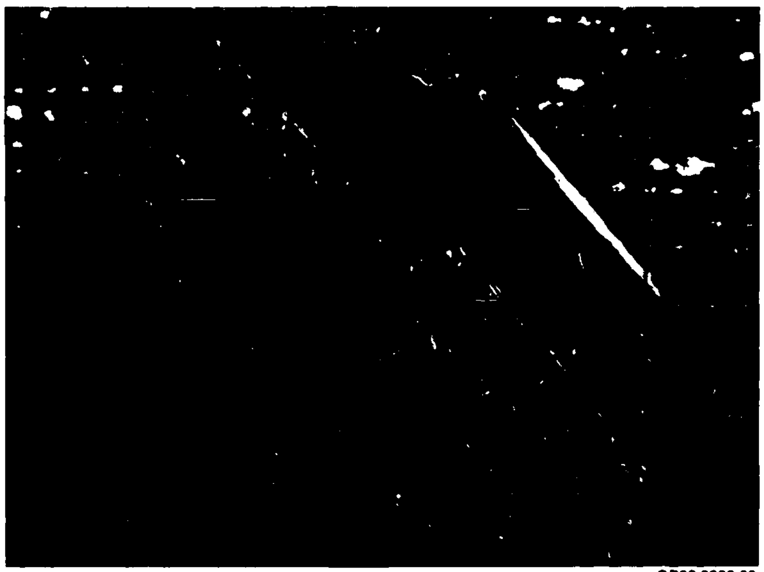

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Figure 17. Anomaly-C, Delaminations, Some Splintering Exit Side (10X)

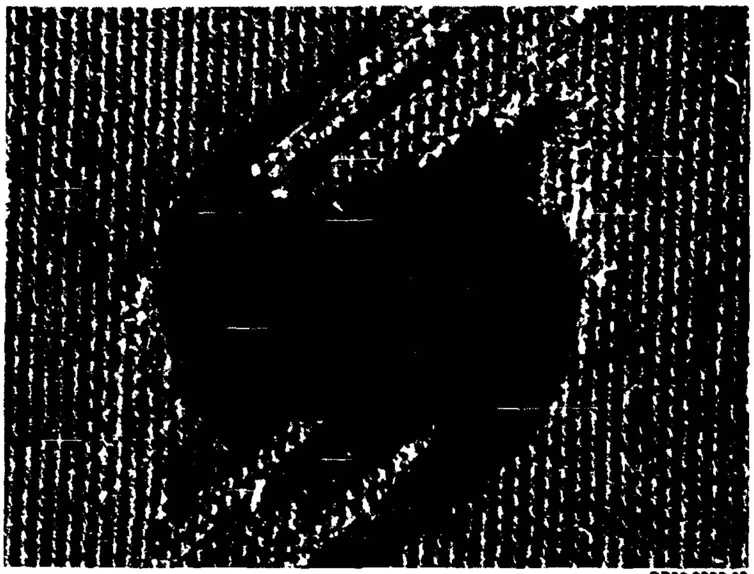

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Figure 18. Anomaly-D, Delaminations, Much Splintering Entrance Side (10X)

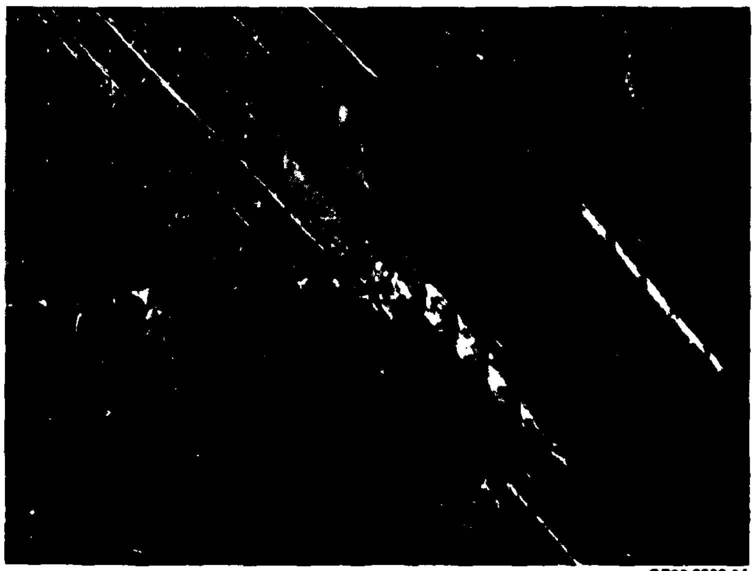

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Figure 19. Anomaly-D, Delaminations, Much Splintering Exit Side (10X)

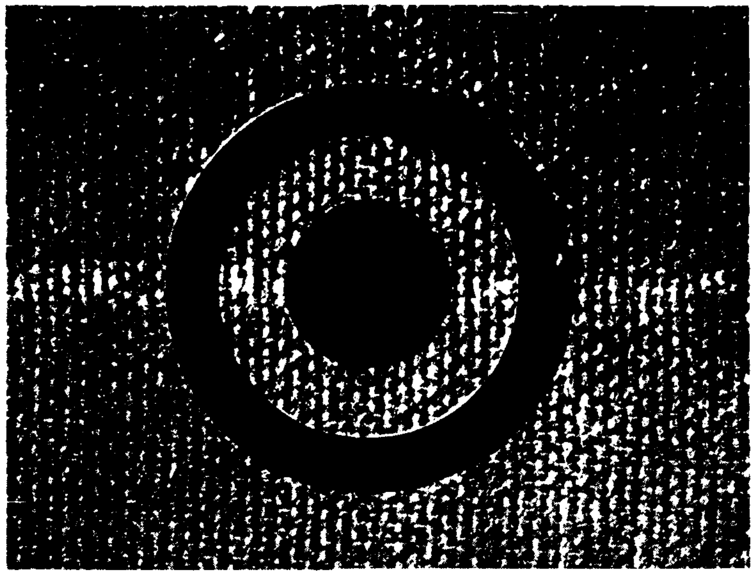

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Figure 20. Anomaly-E, Delaminations Interply Entrance Side (After Drilling) (10X)

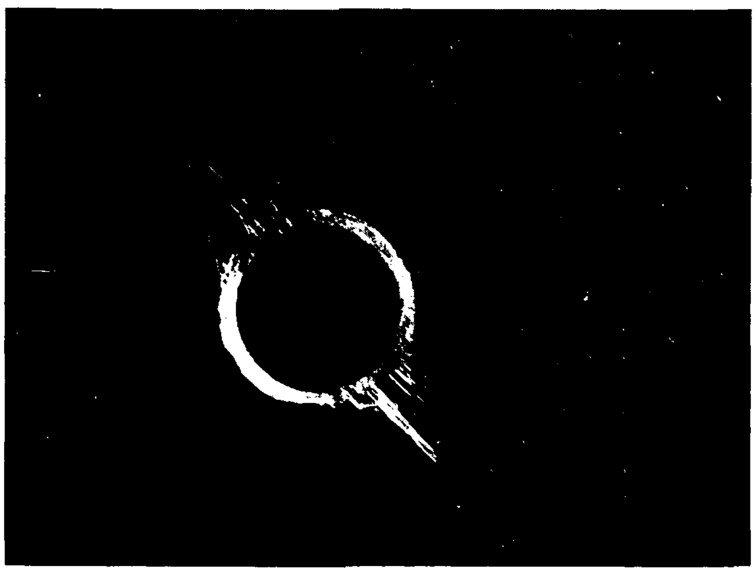

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Figure 21. Anomaly-E, Delaminations Interply Exit Side (After Drilling) (10X)

For simple geometry components, immersion or squirter coupling is generally preferable to contact coupling due to the more uniform coupling and increased ease of automating the scanning and recording of data. Squirter coupling provides a further advantage in that the probability of water intrusion into delaminations or other flaws is reduced. However, the reflector-plate technique provides the best sensitivity and reliability and is optimized with immersion coupling. The reflector plate technique will not provide a good inspection in the area beneath a countersink.

The pulse-echo technique provides the best inspectability in the countersink area when applied from the non-countersunk side. It is amenable to any of the three coupling methods: contact, squirter, or immersion.

In this program, ultrasonic inspection was made using both immersion reflector-plate and contact pulse-echo techniques. The Gr/Ep specimens were immersed in water and supported above an aluminum reflector plate. A lead zirconate titanate search unit with a 2.5 inch focal length was installed and focused on the near (non-countersunk) surface of the test specimens. An external reference standard was positioned adjacent to the specimens and the test sensitivity adjusted to cause 1/8 x 5/8 inch lead tape tabs on the surface of the reference standard to print actual size on the C-scan recording. The specimens were then inspected at the established sensitivity. Indications of all anomalies were noted on the C-scan. For the pulse-echo inspection, an ultrasonic instrument with integral ultrasonic thickness gage was calibrated on a Gr/Ep step wedge. The gate was set to monitor the area between the front and back surfaces of the part and the countersunk area of the hole was inspected.

Flaw indications were noted on the part surface and on the C-scan recording from the reflector plate test. Figures 22 thru 28 are photographs of typical "C" scan recordings of ultrasonic inspection of the acceptable and anomalous holes. As can be seen, ultrasonic inspection is effective in detecting the interply delaminations. Ultrasonic inspection is not effective in detecting splintered delaminations or roughened hole surfaces because of insufficient detail in present print-out systems. Ultrasonic inspection was not effective in detecting overheated hole conditions.

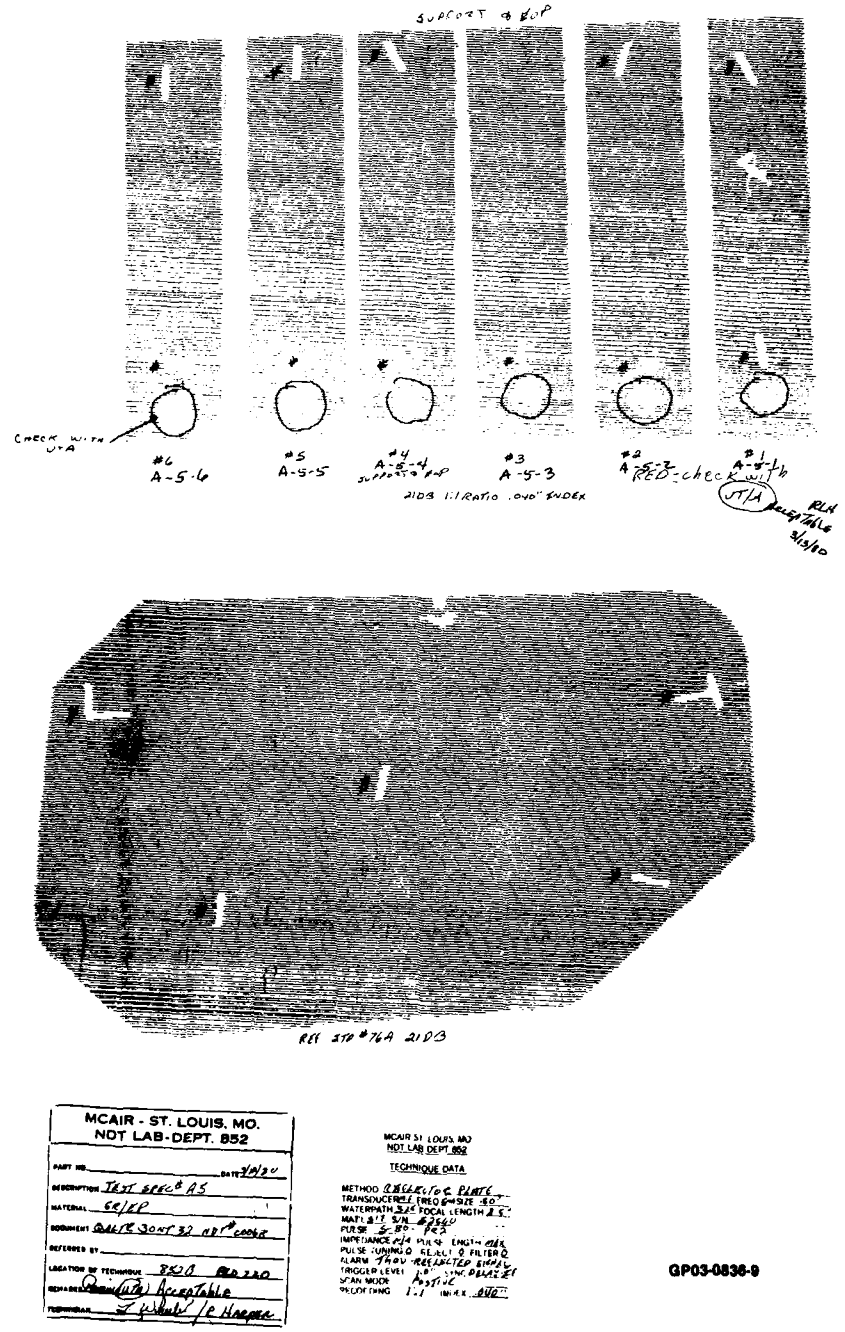

Figure 22. Ultrasonic "C" Scans - Baseline Holes (A)

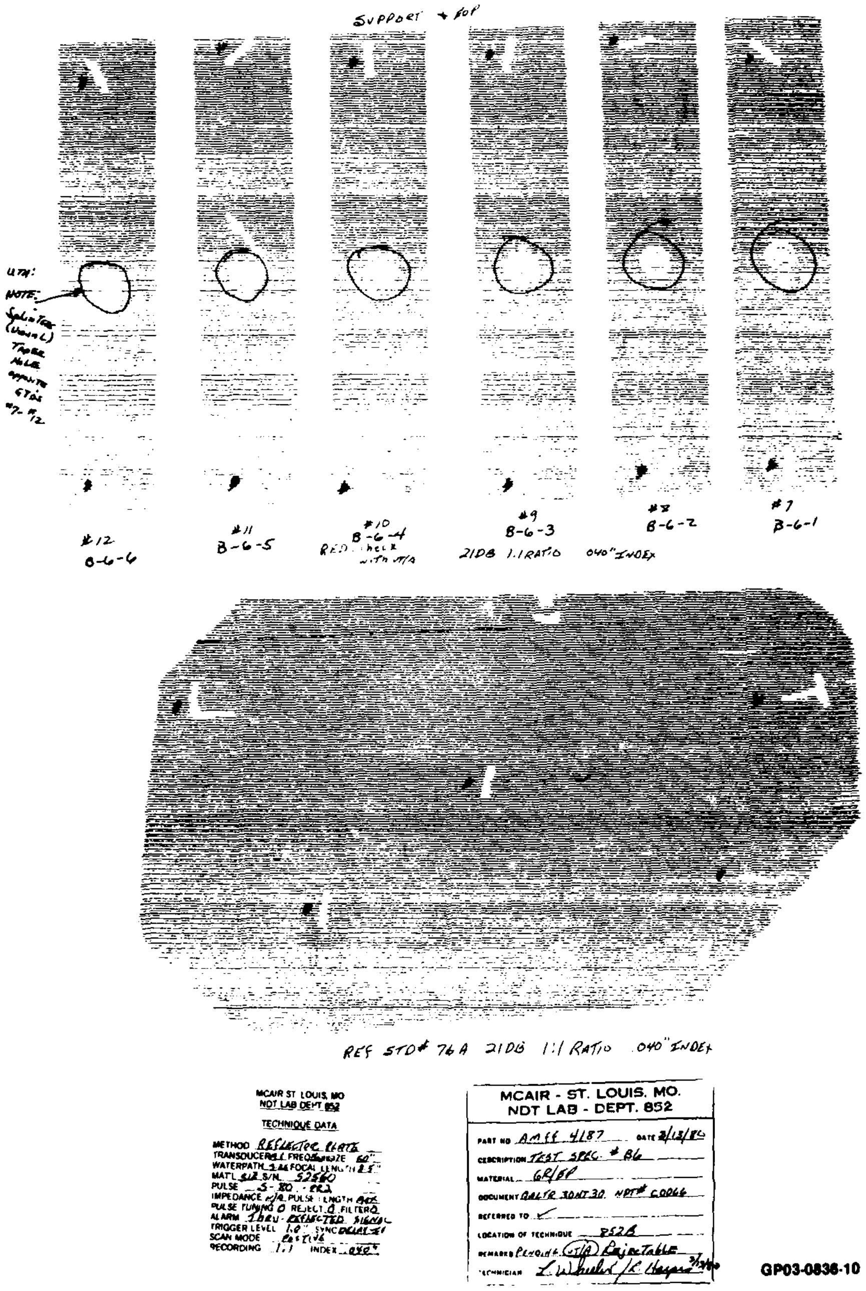

Figure 23. Ultrasonic "C" Scans - Excessive Heat Holes (B)

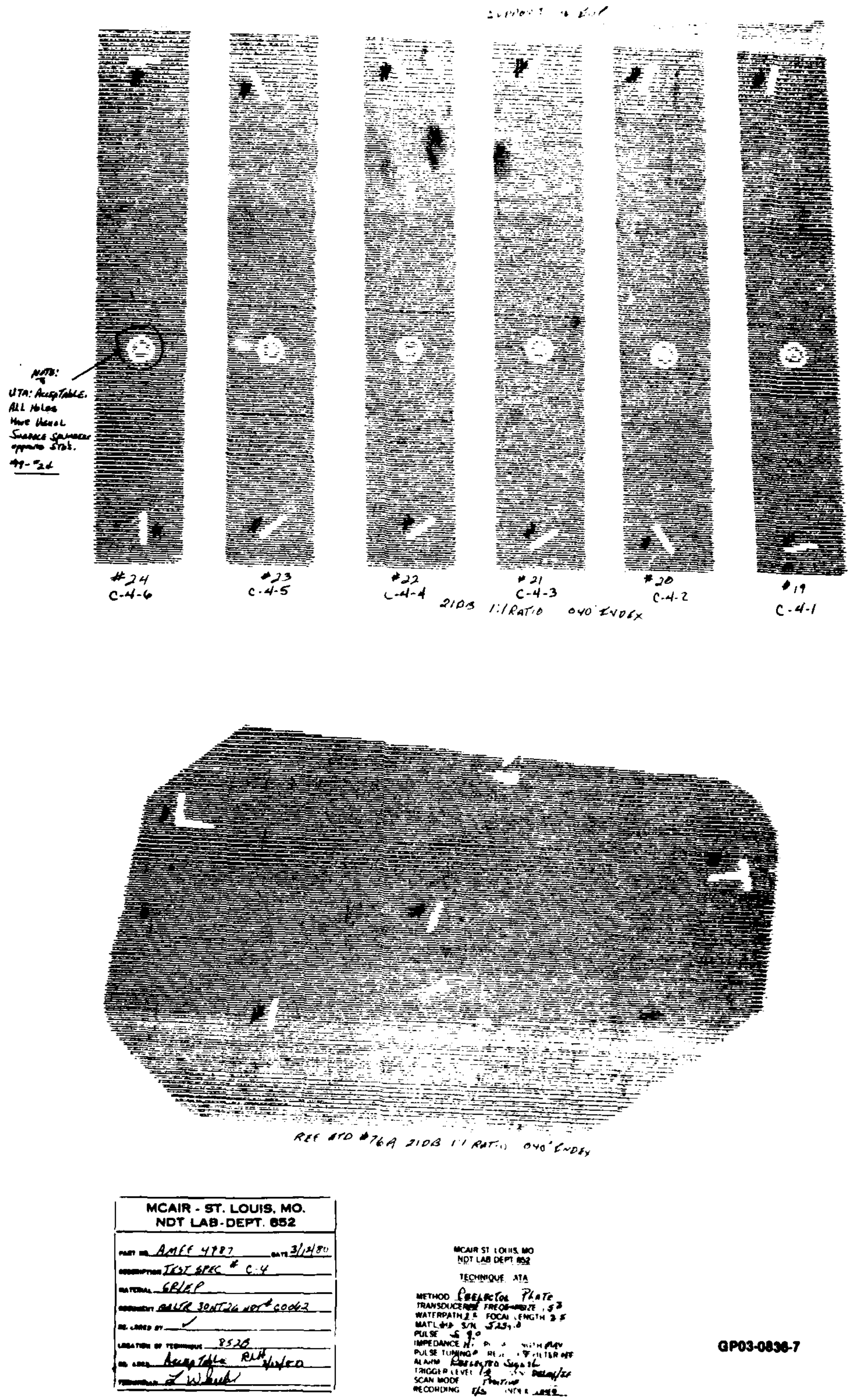

Figure 24. Ultrasonic "C" Scans - Delaminations, Some Splintering (C)

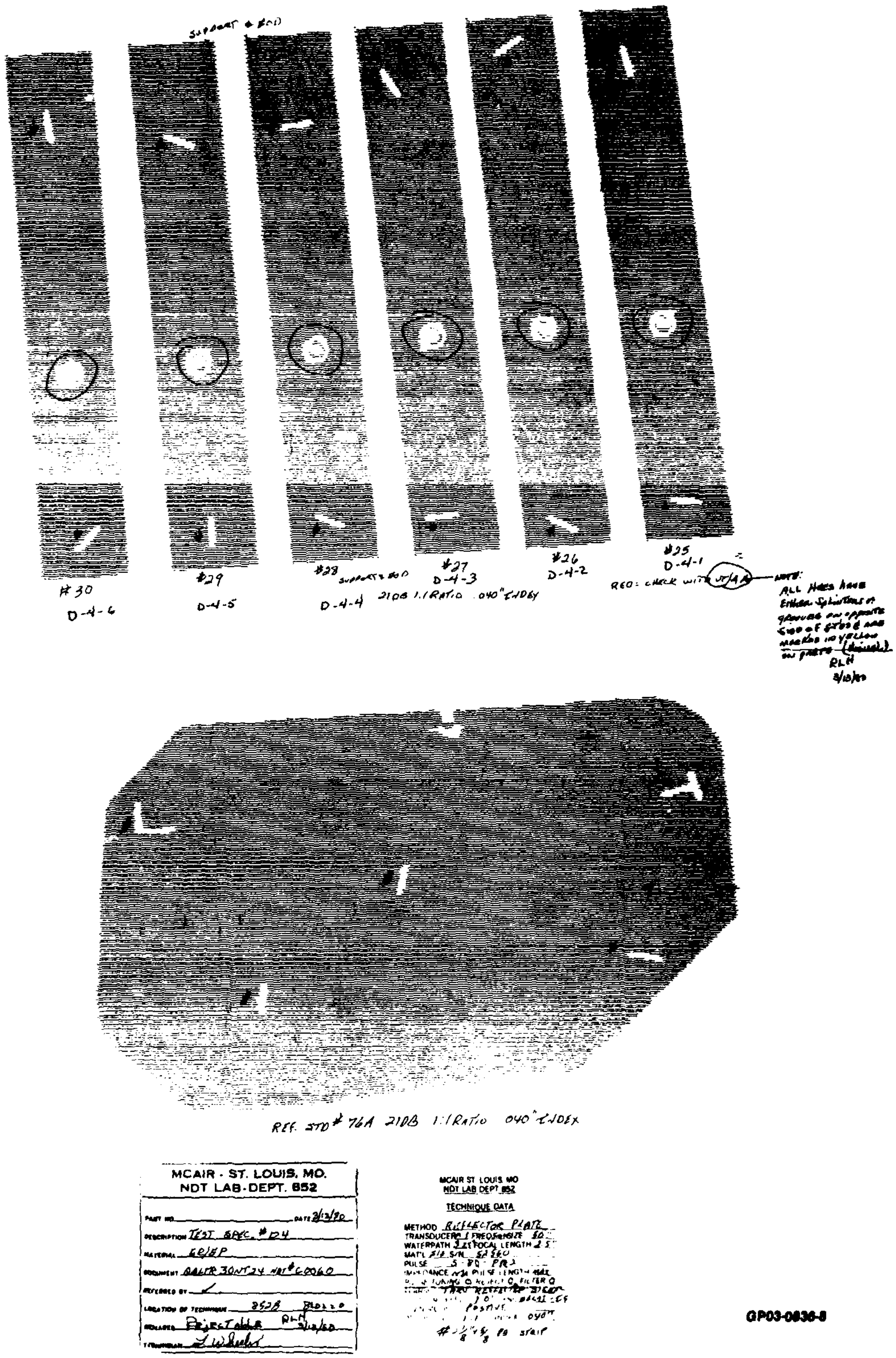

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Figure 25. Ultrasonic "C" Scans - Delaminations, Much Splintering (D)

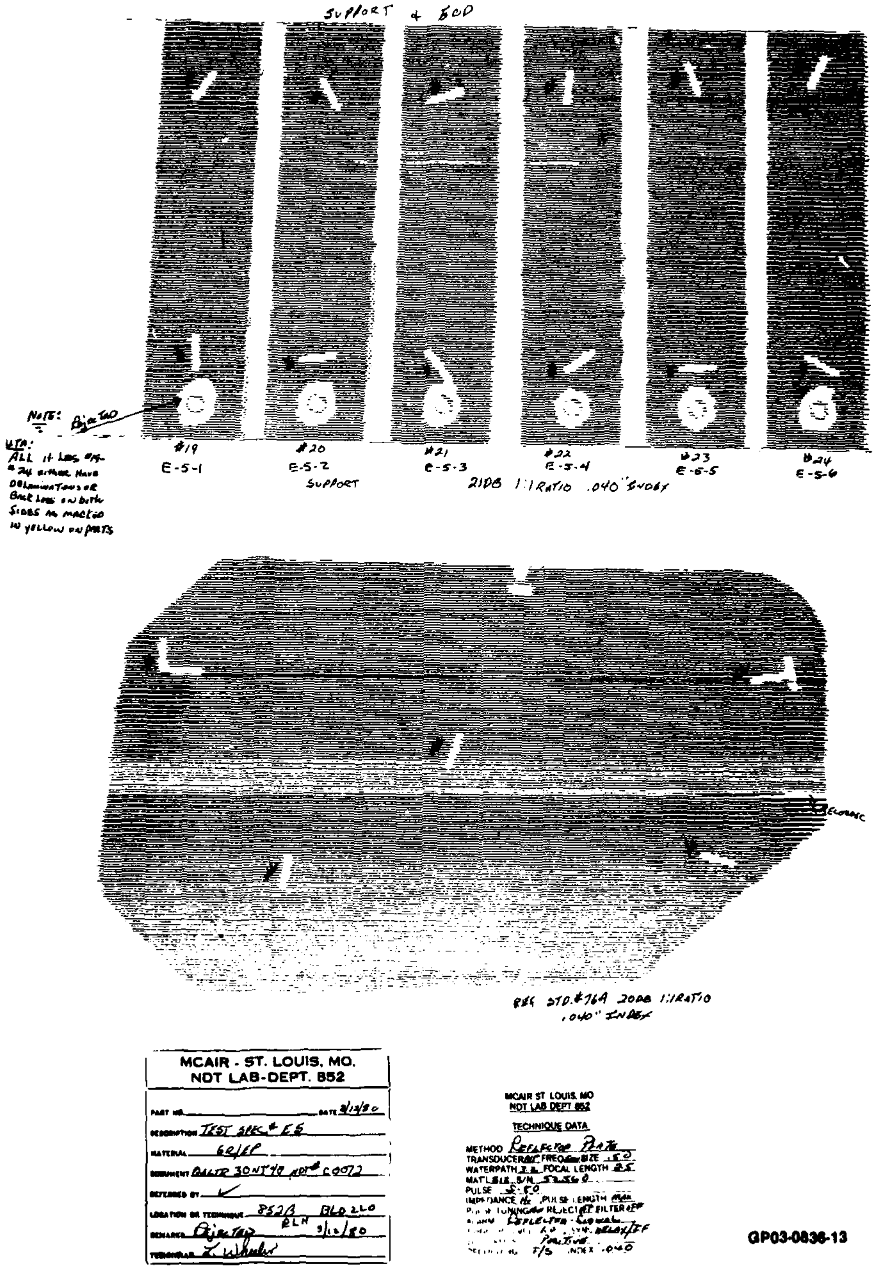

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Figure 26. Ultrasonic "C" Scans - Delaminations, Interply (E)

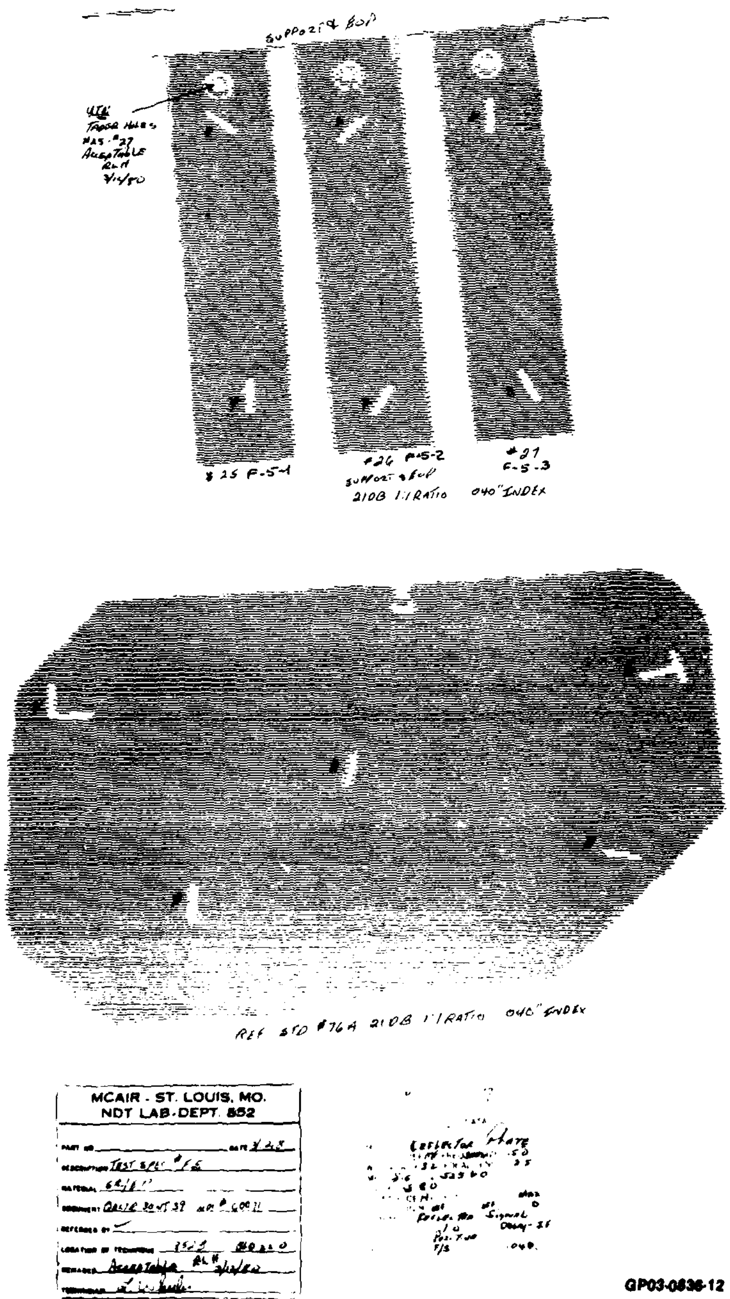

Figure 27. Ultrasonic "C" Scans - Hole Surface Finish > 125 RHR (F)

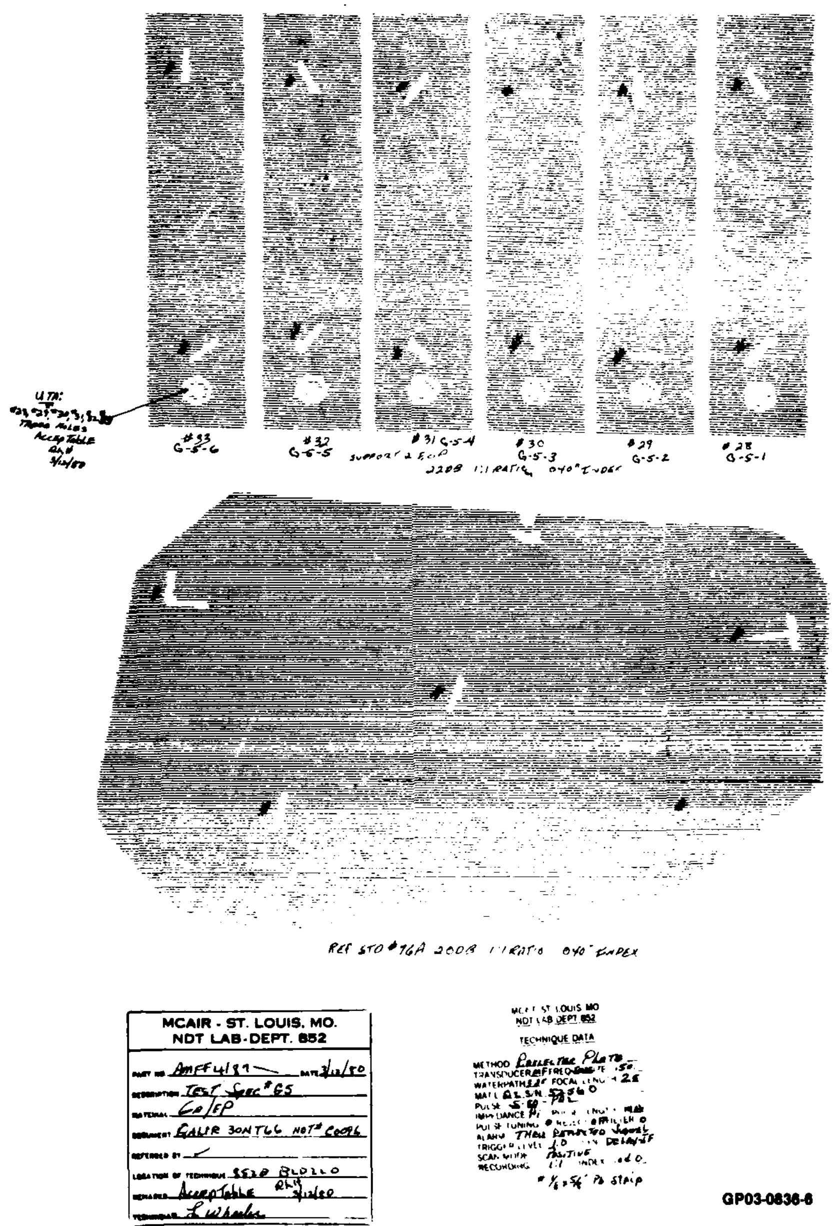

Figure 28. Ultrasonic "C" Scans - Hole Surface Finish > 250 RHR (G)

Radiographic examination of the Gr/Ep test specimens was made using a constant potential X-ray tube set at 15 kV peak. The film cassettes were placed on 0.125 inch thickness vinyl lead to reduce backscattered radiation. The tube head was set 60 inches from the source with current and exposure time adjusted to produce a film density of approximately 2.0 on the H and D curve (sensitometric or film characteristic curve).

The radiographs were reviewed for indications of cracks, ply splintering, foreign objects, and laminate porosity. Figures 29 thru 35 show the radiographs of the baseline holes and holes with anomalies. Only splintering is clearly detectable by X-ray. Other investigations have indicated that radiopaque dye enhances anomalies such as interply delaminations and roughened hole surfaces. However, possible degradation of the laminate around dye enhanced holes during service is not well documented, therefore, this procedure was not used in this program.

3.3 STATIC STRENGTH TESTS

3.3.1 Dry Specimens - Test specimens were produced having desired anomalies. The number of specimens produced for static and fatigue tests is shown in Figure 36. Test specimen dimensions are shown in Figures 37, 38, and 39.

The dry test specimens were static tested to failure. The test matrix used for the unloaded and loaded hole static tests was shown in Figure 2.

A Model 81 Material Test System (MTS) testing machine with hydraulic grips was used for all of the dry static tests. Head deflection was measured by an integral electronic system. To prevent buckling during the compression tests, steel guide plates were clamped to the specimens as shown in Figure 39. The loading rate used for all static tests was 2500 pounds per minute.

An MTS 632.01 compliance gage was attached to the specimen for loaded hole tests as shown in Figure 40. The gage closely measures the specimen deflection in the area of the loaded hole.

All specimens were instrumented with 350 ohm Micromeasurement strain gages, adhesively bonded to the Gr/Ep specimens. The gages were positioned as shown in Figures 37 and 38. Tension head bolts were initially installed in all of the unloaded hole specimens and torqued to 70 inch-pounds. The loaded hole specimens were also torqued to 70 inch-pounds, using hex-head bolts with conical-head bushings, as shown in Figure 41. This testing setup was used for the loaded hole static tests to eliminate bending of the specimens when tension loads were applied.

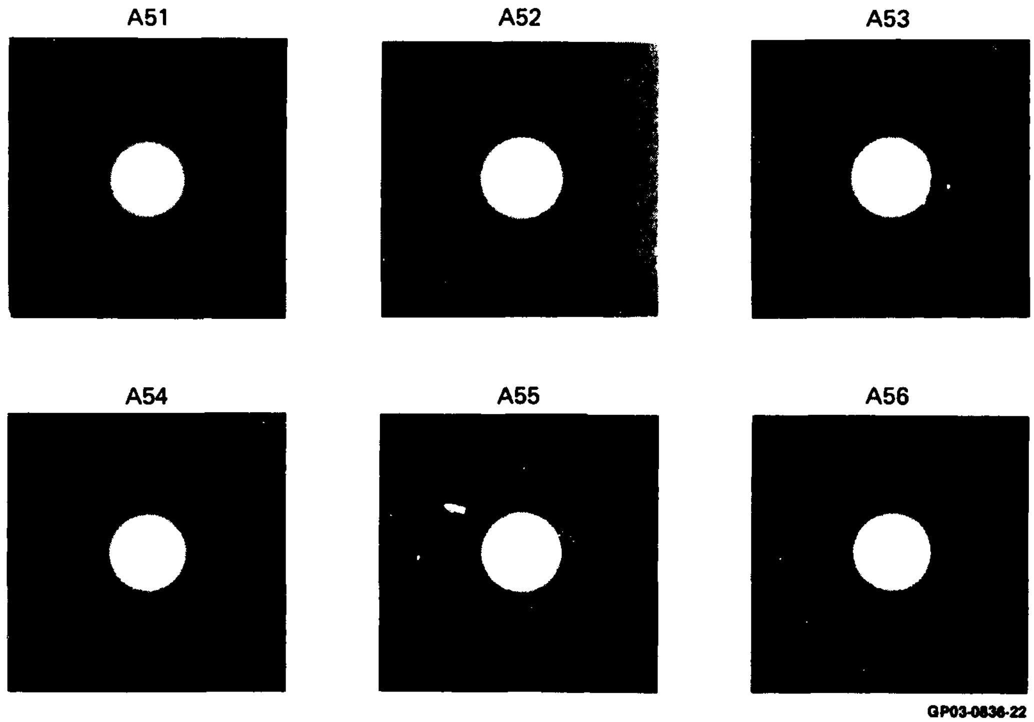

Figure 29. Radiographs - Baseline Holes (A)

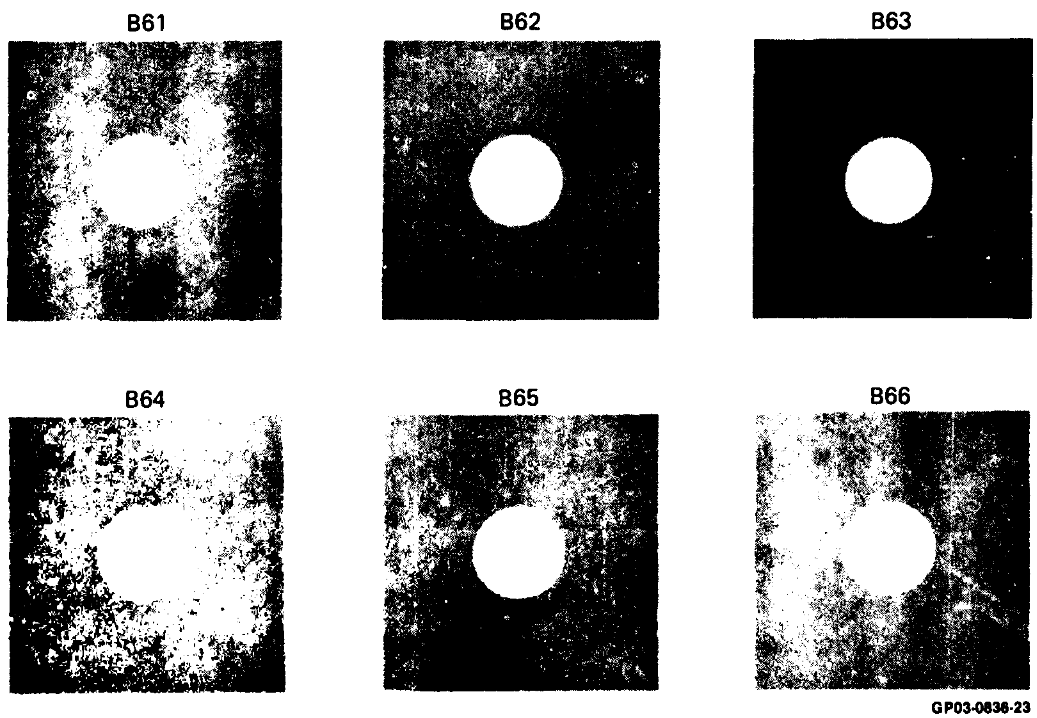

Figure 30. Radiographs - Excessive Heat Holes (B)

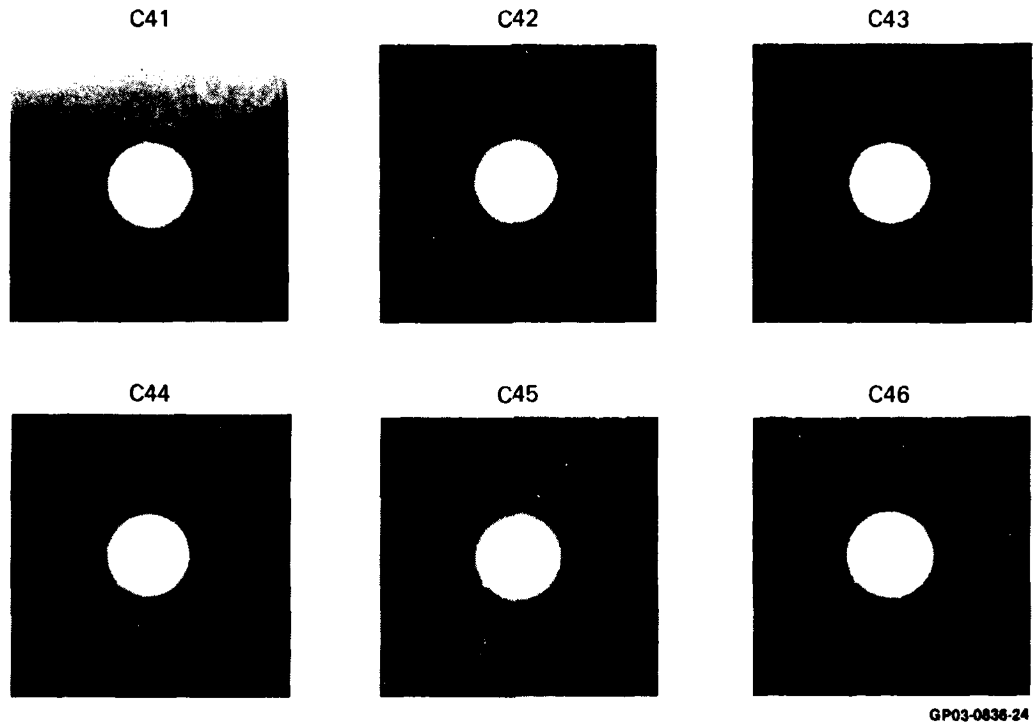

Figure 31. Radiographs - Delaminations, Some Splintering (C)

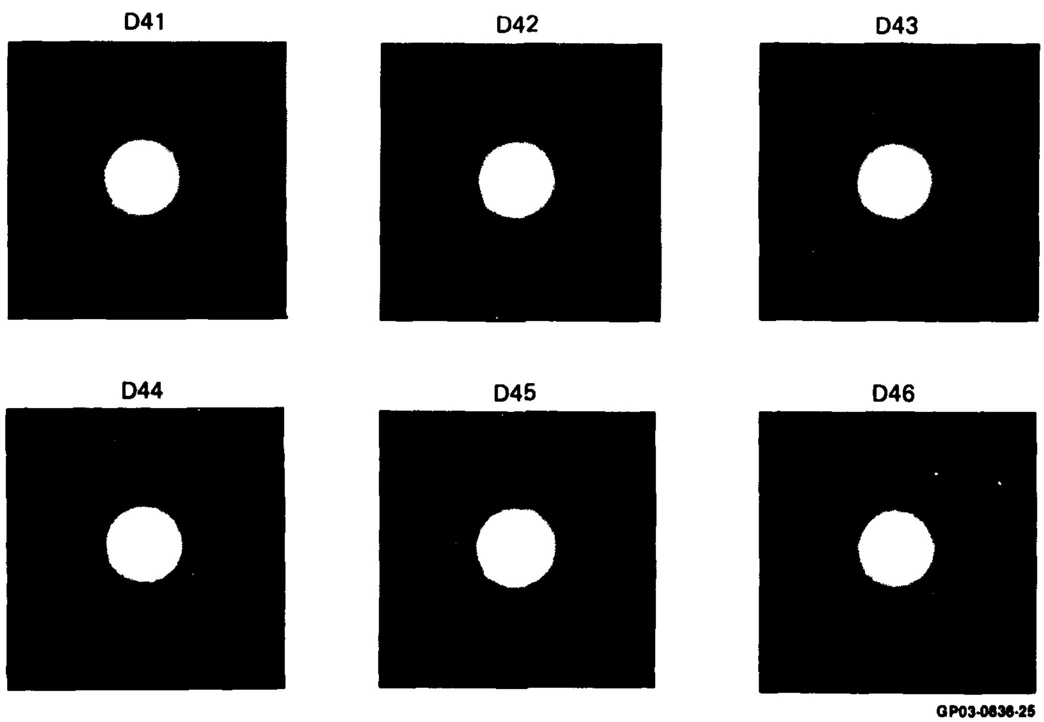

Figure 32. Radiographs - Delaminations, Much Splintering (D)

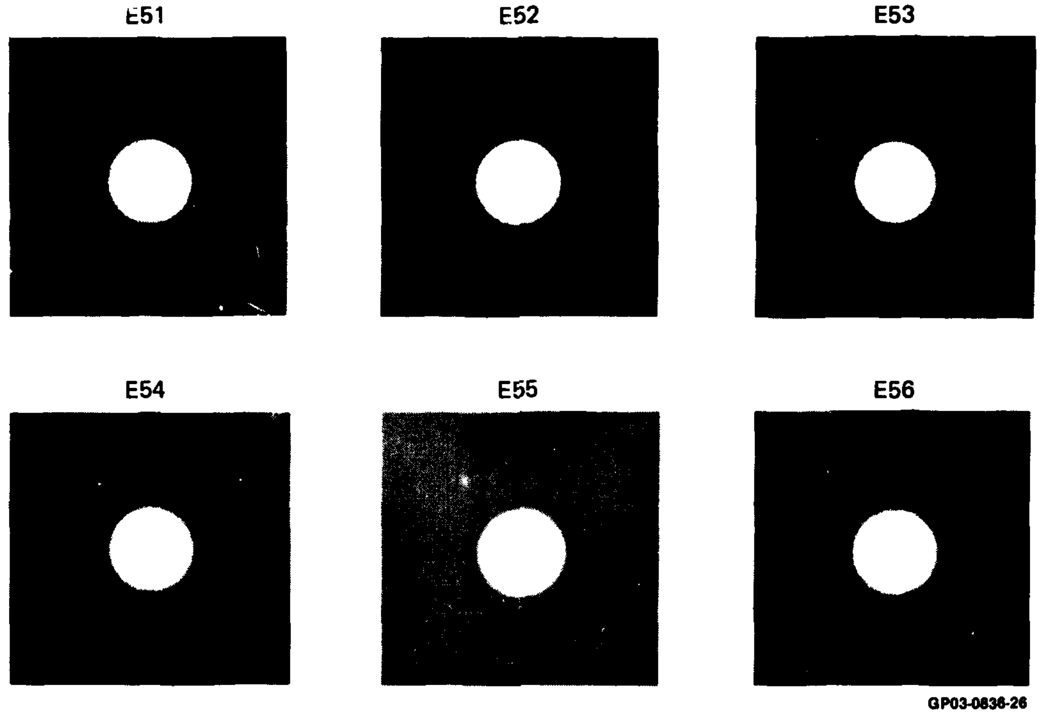

Figure 33. Radiographs - Delaminations, Interply (E)

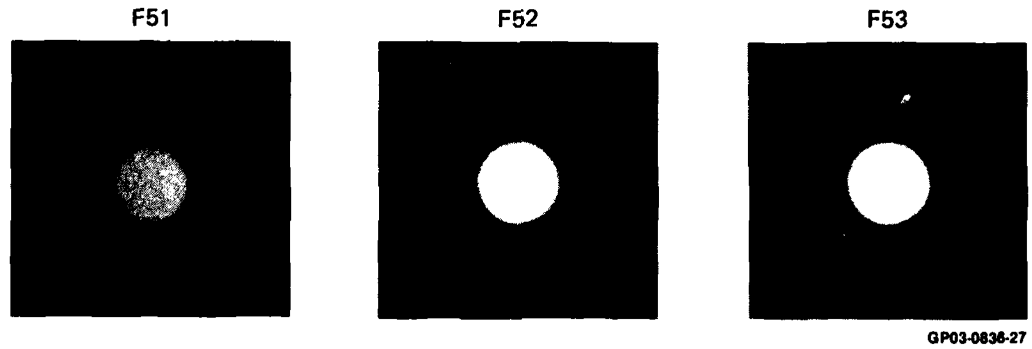

Figure 34. Radiographs - Hole Surface Finish > 125 RHR (F)

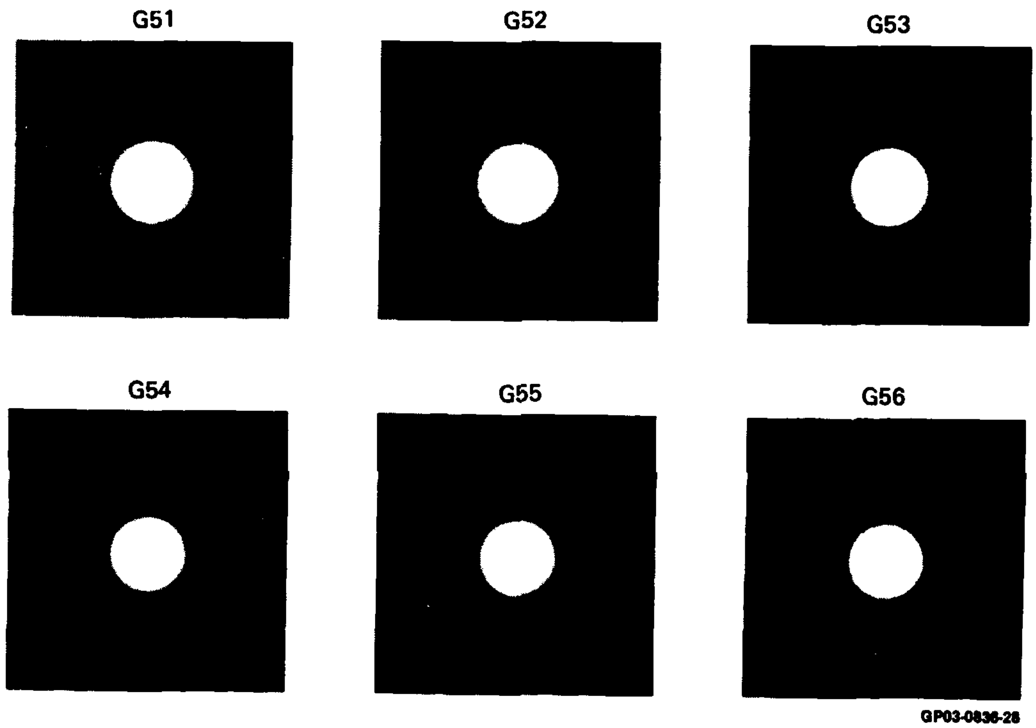

Figure 35. Radiographs - Hole Surface Finish > 250 RHR (G)

Hole Condition	Number of Specimens	Figure Number
(A) Baseline	9 6 6	37 38 49
(B) Excessive Heat	9 6 6	37 38 49
(C) Delamination, Some Splintering	6 3 –	37 38 49
(D) Delamination, Much Splintering	6 3 –	37 38 49
(E) Delamination, Interply	9 6 6 ⚠1	37 38 49
(F) Surface Finish, 125 RHR	6 3 –	37 38 49
(G) Surface Finish, 250 RHR	9 6 6 ⚠1	37 38 49

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⚠1 Drilled only after static tests were completed

Figure 36. Anomaly Test Specimens

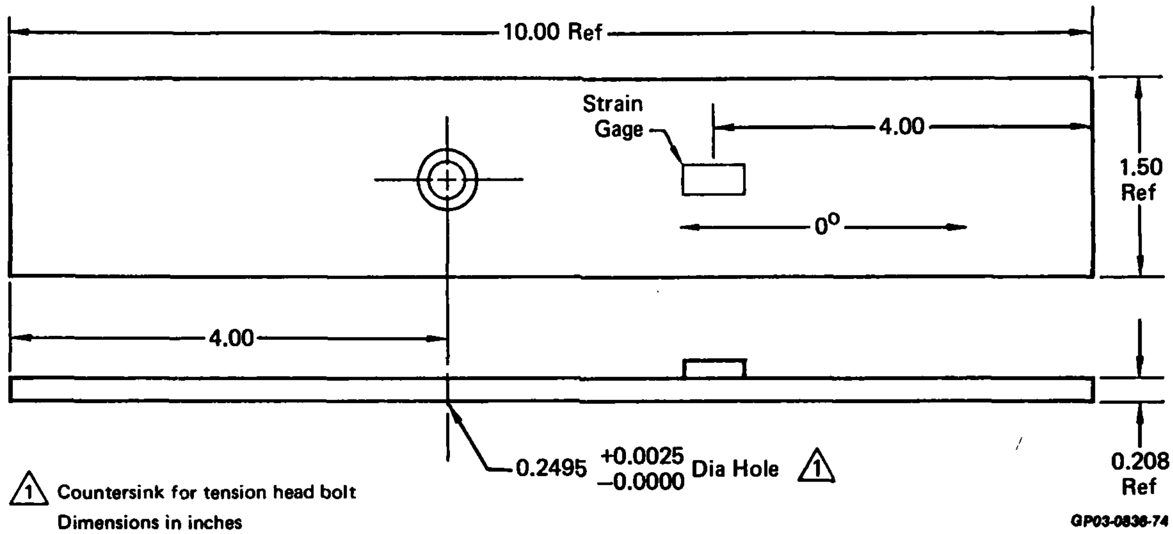


Figure 37. Test Specimens - Unloaded Hole, Static Test (UHST)

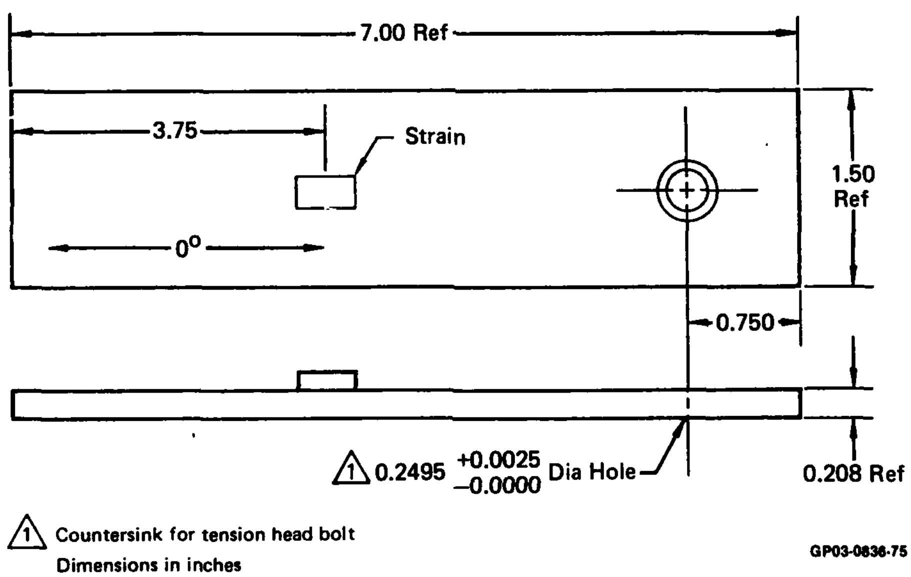
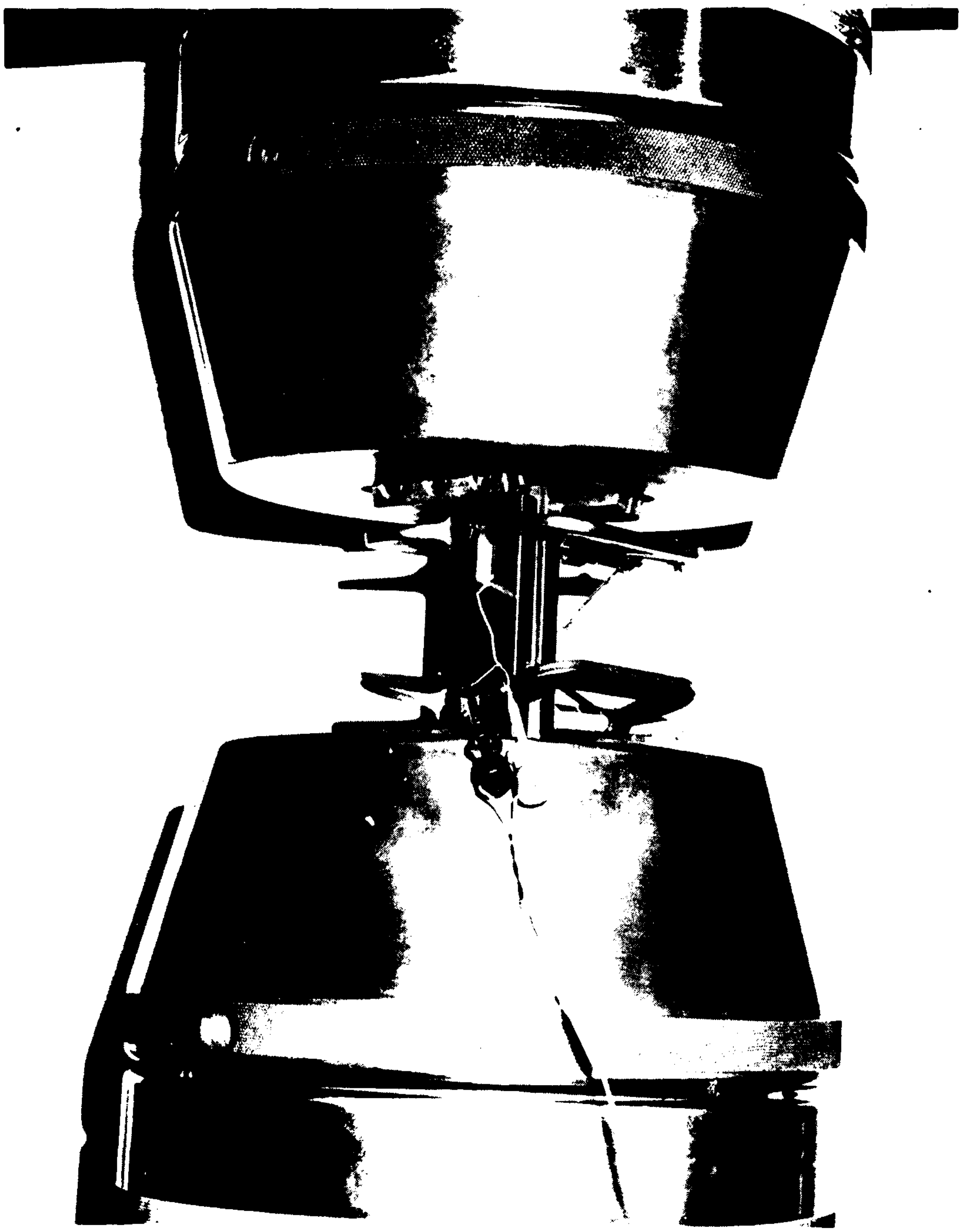
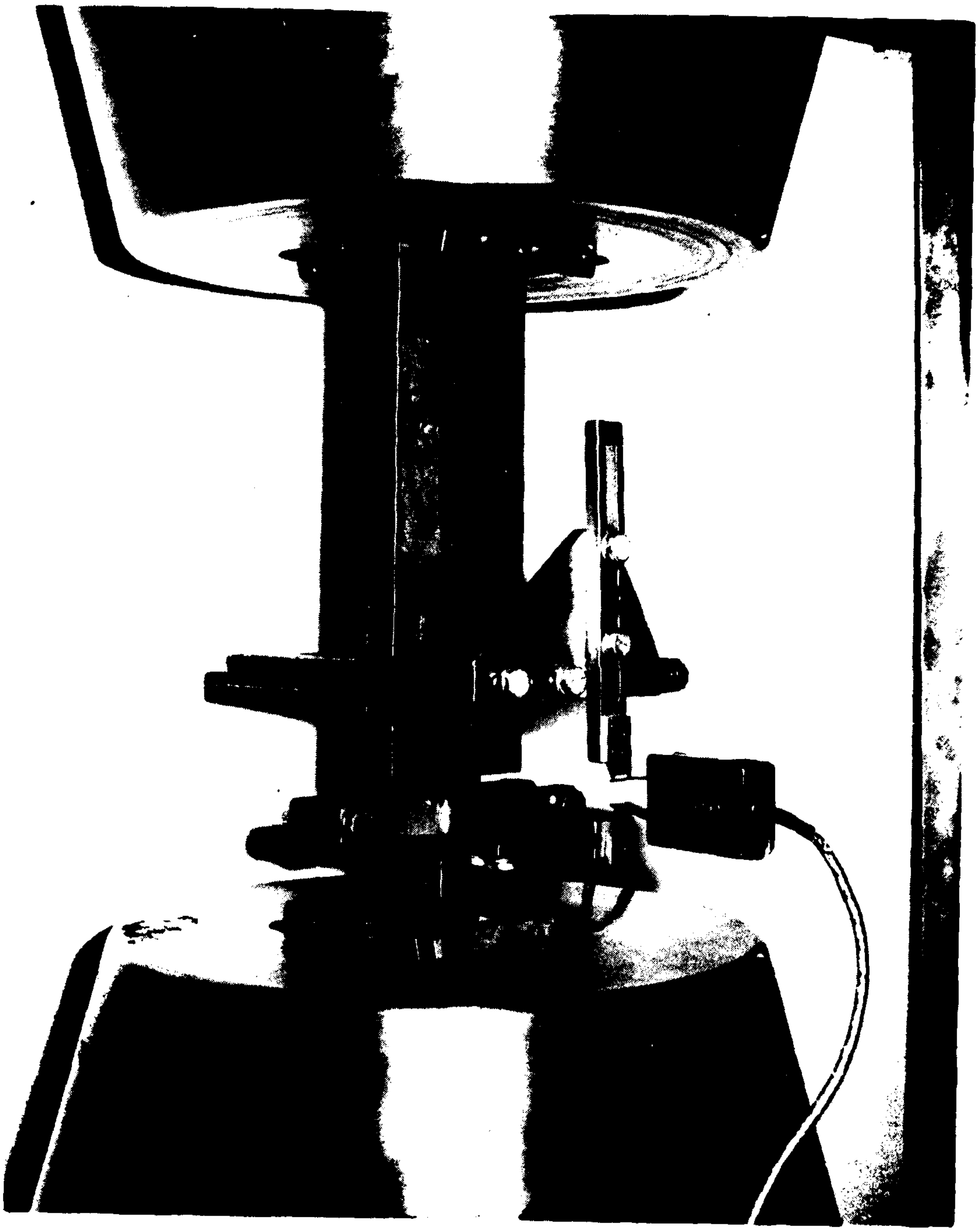


Figure 38. Test Specimen - Loaded Hole, Static Test (LHST)



GP03-0836-71

Figure 39. Compression Static Test Setup



GP03-0838-72

Figure 40. Loaded Hole Static Test Setup

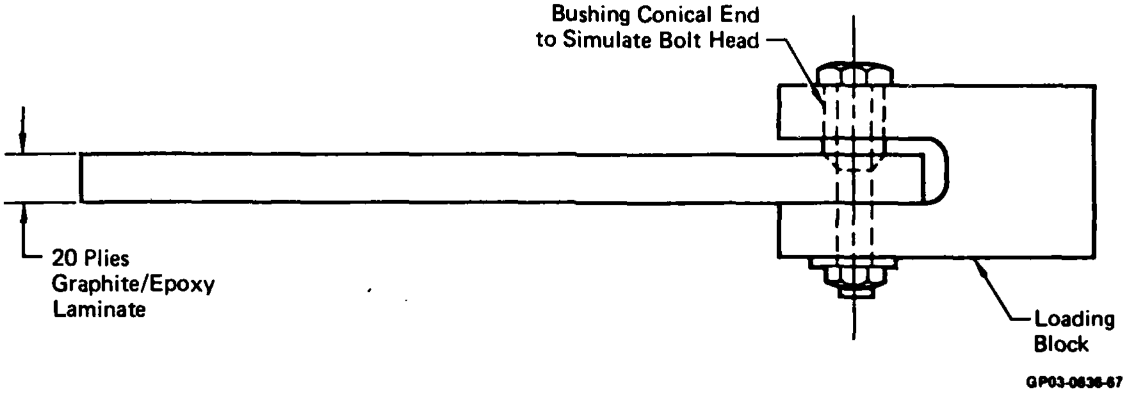


Figure 41. Test Specimen with Loading Block

Results of the static tests of dry specimens are shown in Figure 42. Detailed results are given in the Appendix. The data presented in Figure 42 indicates that the anomalies in the holes do not affect unloaded hole tension strain more than 4%. The same tensile results can be seen for the loaded holes.

In the case of compression, loads transferred through the fasteners alleviated stress concentration effects normally associated with flaws in holes. This caused essentially unnotched laminate failures at the gripped area instead of at the areas around the holes. The fasteners were therefore removed from these specimens and the compressive strength data obtained. Only in static compression tests, with no fasteners in the holes, was there any noticeable degradation in static strengths and this was only in the case of interply delamination, where static strength decreased about 17%. (The same condition does not cause excessive degradation when specimens are tested in tension, as the interply delaminations apparently close up). Figures 43, 44, and 45 show the comparative average values of data obtained.

All unloaded hole specimens were compared in terms of the directly recorded strain values at failure. Strain data reporting assures that effects of variations in hole quality on laminate strength are not masked by the variations in geometry which may bias data manipulation required to convert strain to stress. (For the layup tested, stress values may be approximated by multiplying strains by the specimen axial modulus of 8.3 x 10^6 psi).

3.3.2 Wet Specimens - Wet specimens were also statically tested in the unloaded and loaded fastener conditions at 250°F. Test equipment and methods used were the same as that used during the dry specimen tests. The 250°F test environment was obtained by enclosing the MTS grips with a Mylar jacket. A forced air electrical preheater then heated the enclosed jacket area. The air temperature was monitored and maintained with a temperature controller. Temperature was held for 10 minutes prior to loading the specimens. The wet specimens had been moisture conditioned per the schedule shown in Figure 46 to a 1% moisture content. The two stage conditioning is required to obtain a uniform moisture content throughout the specimen thickness. Figure 47 shows the comparative average values of data obtained. Detailed results are given in the Appendix. Only the excessive heat specimens showed any appreciable degradation of static strength when tested under these conditions. Figure 48 shows the summary of the results of all static tests completed.

Hole Condition	Unloaded Hole		Loaded Hole	
	Strain (Tensile) μ in/in	Strain (Compressive) μ in/in	Strain (Tensile) μ in/in	Bearing Stress ⚠2 (Tensile) ksi
Baseline	5742	6603*	3223	158
Excessive Heat	5487 ⚠1 (.96)	6988* (1.06)	3353 (1.04)	165 (1.04)
Delaminations: Some Splintering	5562 (.97)	7088* (1.07)	3222 (1.00)	161 (1.02)
Delaminations: Much Splintering	5748 (1.00)	7023* (1.06)	3135 (.97)	159 (1.01)
Delaminations: Interply	5858 (1.02)	5453* (.83)	3008 (.93)	151 (.96)
Hole Surface Finish > 125 RHR	5658 (.99)	6355* (.96)	3155 (.98)	156 (.99)
Hole Surface Finish > 250 RHR	5543 (.97)	6422* (.97)	3265 (1.01)	162 (1.03)

* No fastener in hole

⚠1 5487 Average of results } Typical
(.96) % of baseline

⚠2 $F_x^{bru} = \frac{P^u}{(d)(t)}$

where: P^u = ultimate load
d = fastener diameter
t = specimen thickness

GP03-0836-70

Figure 42. Static Test Data

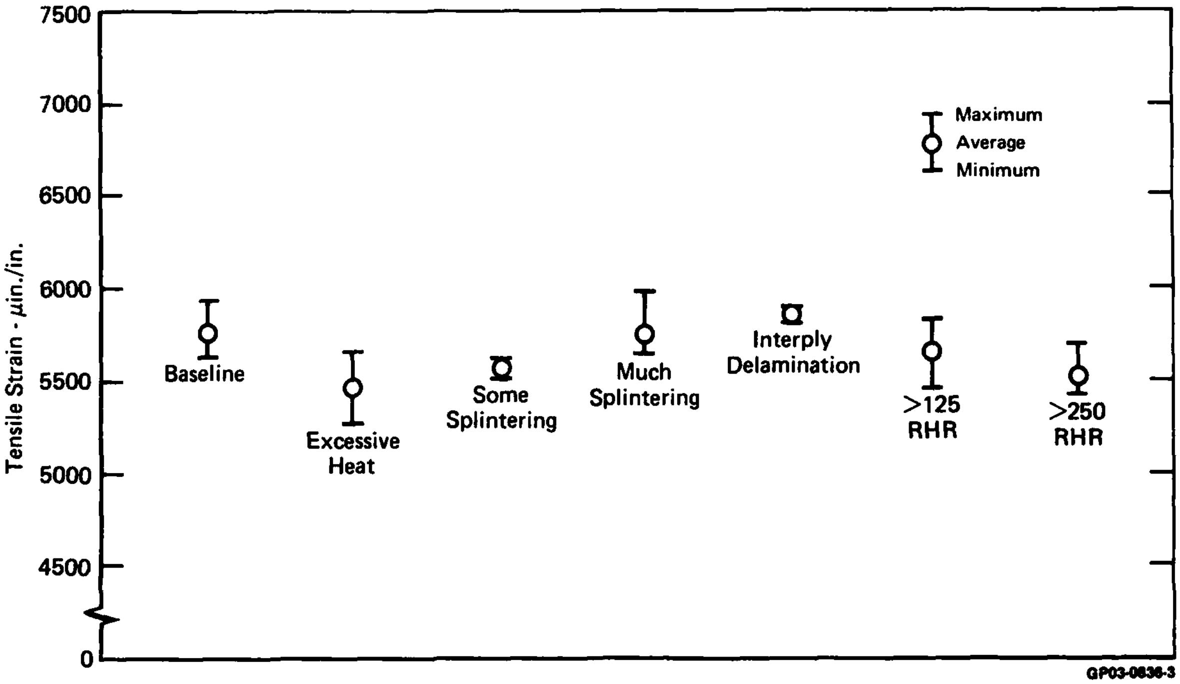


Figure 43. Unloaded Hole - Tensile Test Data

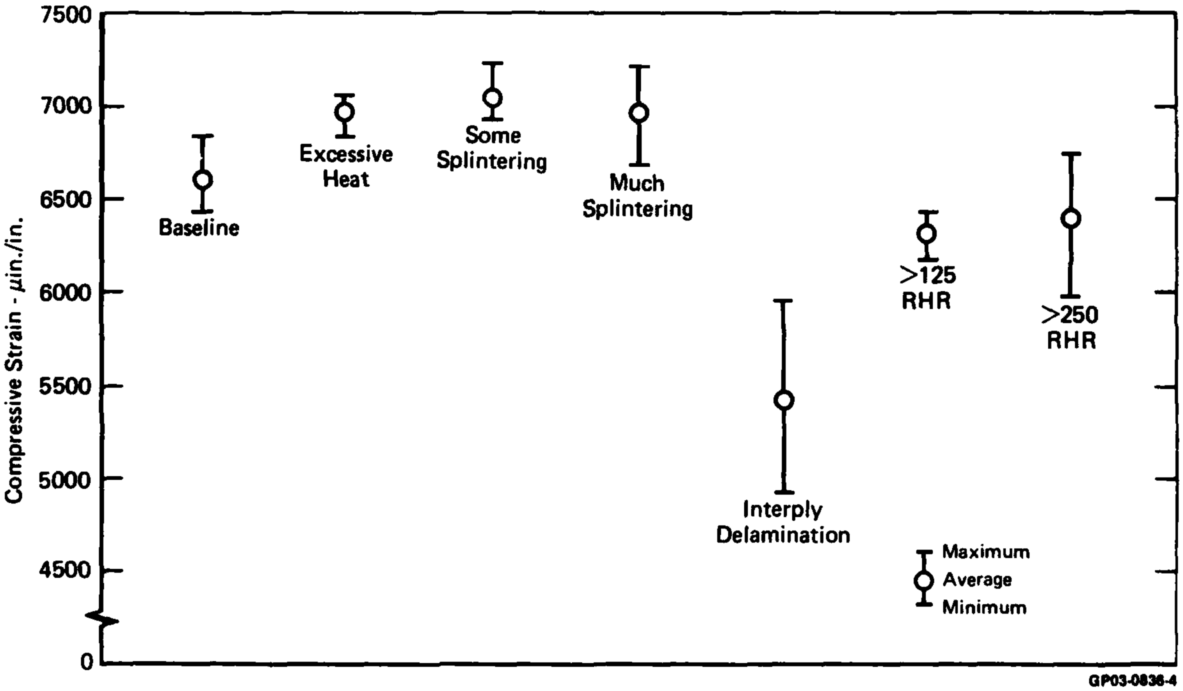


Figure 44. Unloaded Hole - Compressive Test Data

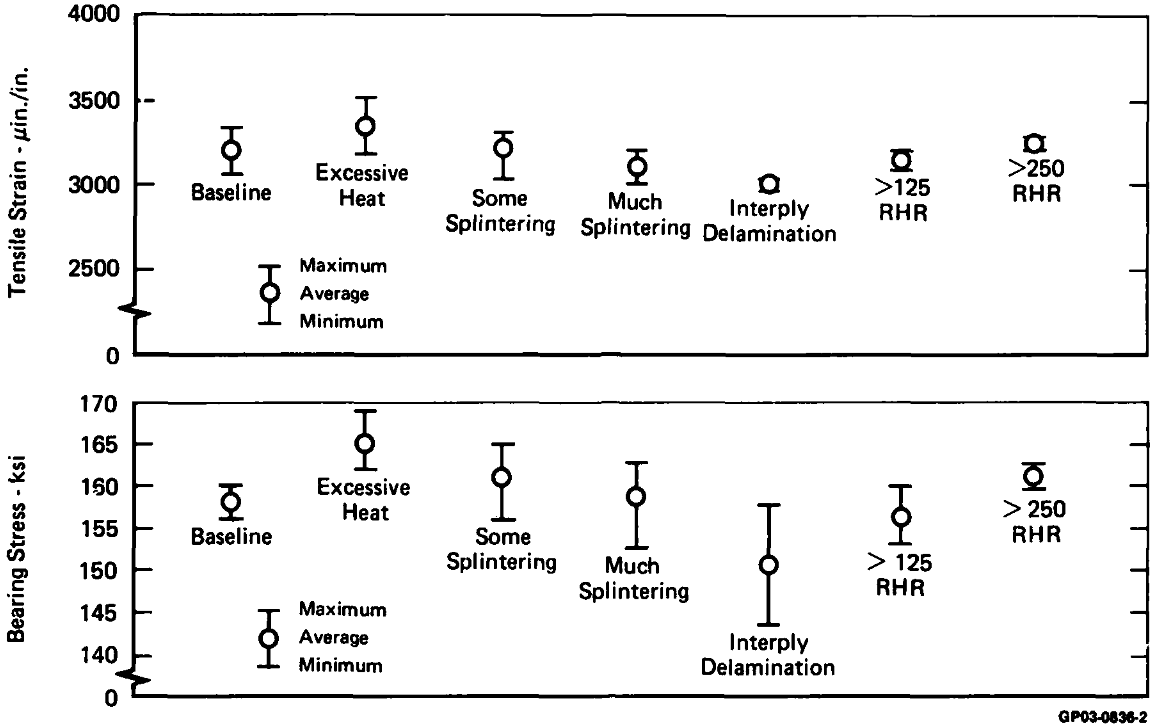


Figure 45. Loaded Hole - Tensile Test Data

Stage	Conditioning Temperature (°F)	Relative Humidity (%)	Exposure Time (days)	Final Weight Gain (%)
1	180	95	45	1.10
2	180	70	15	1.00

GP03-0836-73

Figure 46. Specimen Moisture Conditioning Schedule

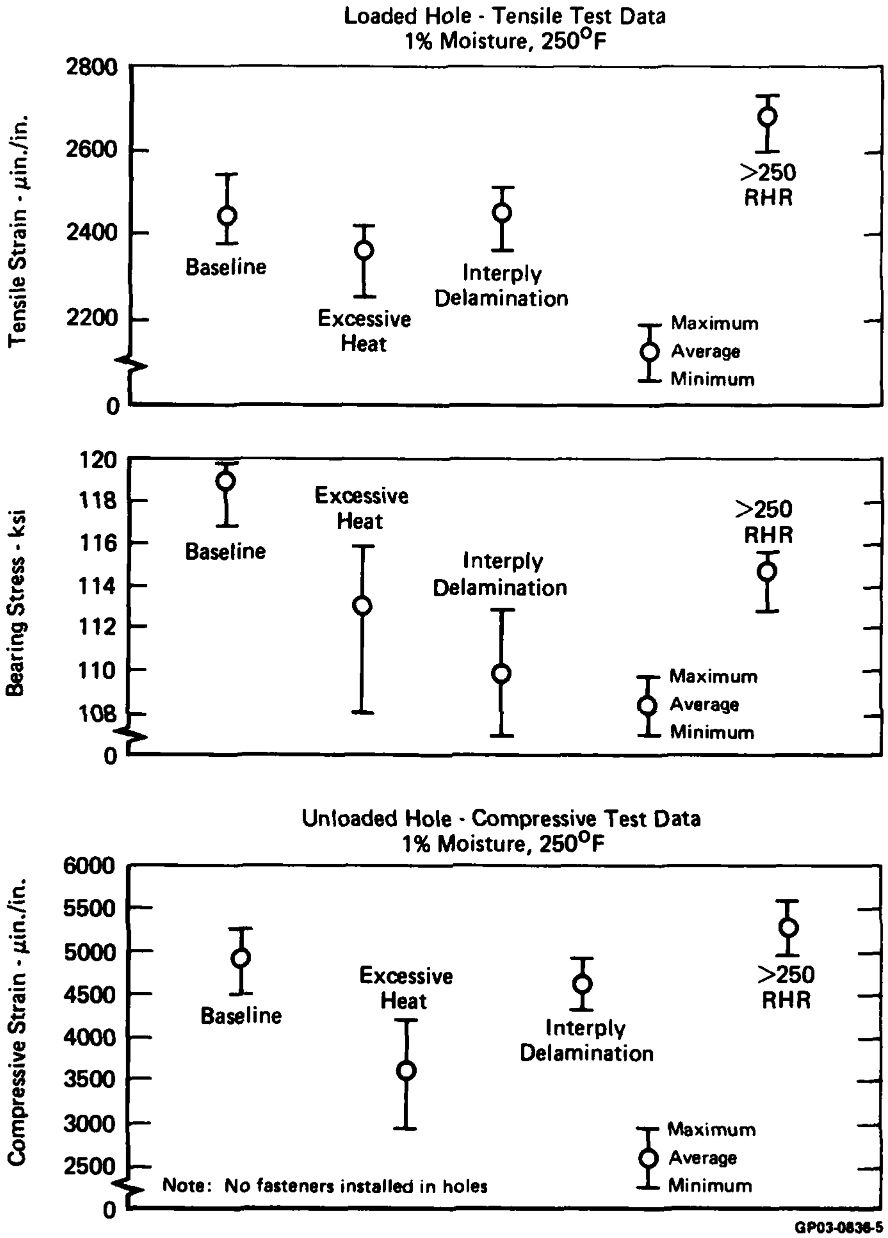


Figure 47. Wet Specimen Test Data

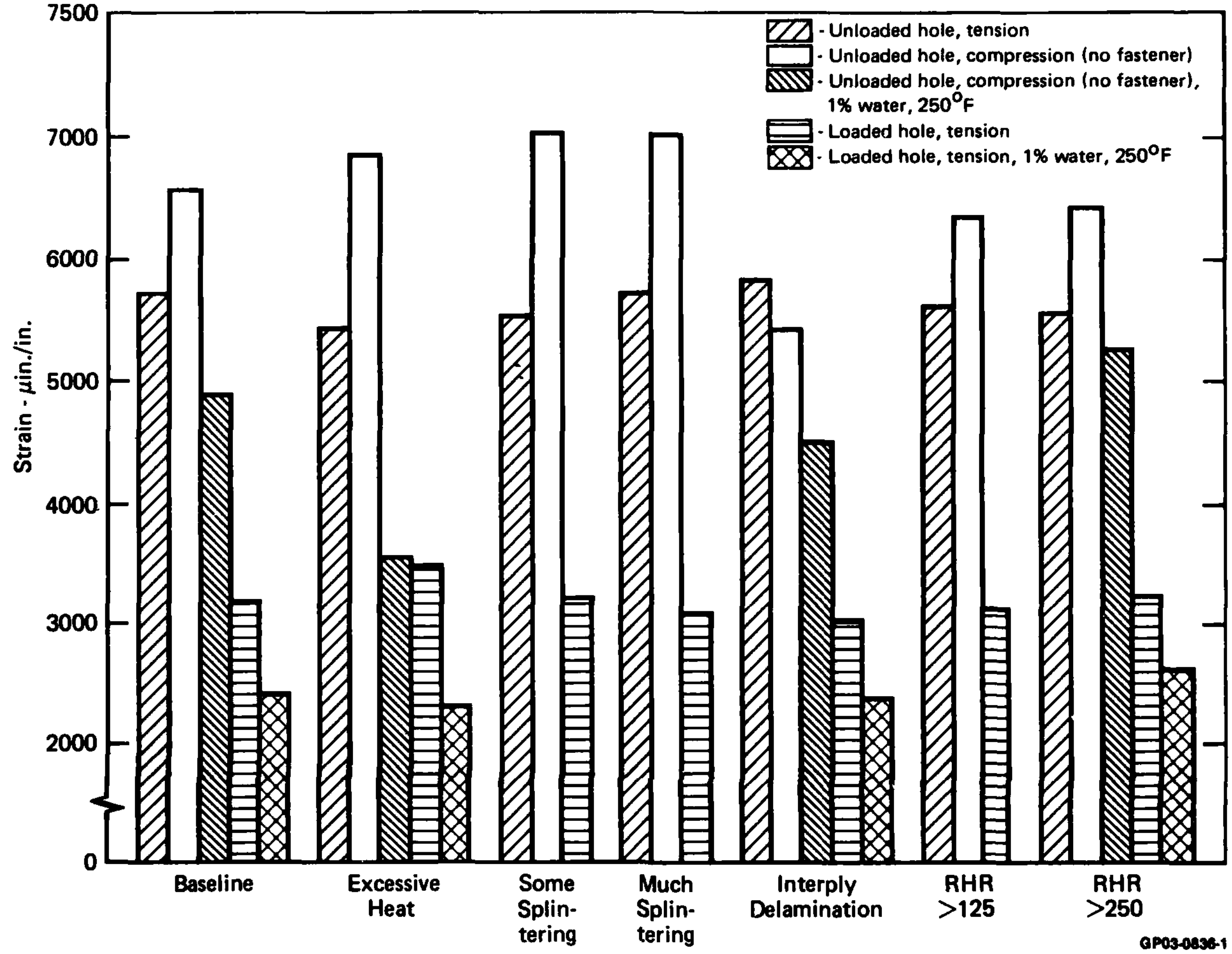


Figure 48. Summary of Static Tests (Hole Preparation Gr/Ep)

3.4 FATIGUE STRENGTH TESTS - The number of dry specimens tested in fatigue is shown in Figure 2. The configuration is shown in Figure 49. Tension head bolts were installed in all specimens and torqued to 70 inch pounds. Constant amplitude fatigue testing of the dry specimens was accomplished at room temperature with a maximum tension to minimum compression load ratio of -1. The test limit load was specified as 12,550 pounds representing 75% of the static compression failing load and 87% of the static tension failing load of the baseline specimens previously tested. The resulting strain in tension and compression was about 4950 μ inch/inch. Figure 50 and Figure 51 show the results of these tests. Detailed results are given in the Appendix. The cycling rate was restricted to 5 cycles per second to maintain fastener temperature below 100°F.

As in the static compression tests of dry specimens, the interply delamination anomaly caused the most degradation in fatigue life. Cycles-to-failure for baseline specimens were low due to the severe test limit load used for screening purposes in the program. All specimen failures occurred consistently in the hole and fastener areas indicating similar failure modes for all conditions. The data spread was the greatest for the baseline specimens. This is as it should be as anomalies were not present to initiate failure in a specific area.

3.5 FASTENER INSTALLATION TESTS - Fastener installation test specimens were fabricated from laminates identical to those used in the strength tests. Figures 52 and 53 show the specimens used. All holes were produced in the same manner as the baseline holes produced for strength tests. Both 5/32 inch rivets and 1/4 inch nominal diameter bolts were used. Bolts were torqued to approximately 70 inch-pounds. Figure 54 shows the combinations of fasteners evaluated and Figures 55 and 56 are photographs of the actual fastener combinations that were installed.

3.5.1 Nondestructive Testing - Prior to installation of the fasteners, radiographic and ultrasonic inspections of the specimens were made using the same techniques previously discussed in Section 3.2. These tests indicated the hole quality to be acceptable to production requirements. After installation of the fasteners the specimens were again nondestructively tested.

Radiographic inspection techniques were not used after fastener installation because the fasteners, aluminum plates, and titanium back-up shims masked the laminates in the area where anomalies might occur. Special ultrasonic techniques were developed to inspect these areas.

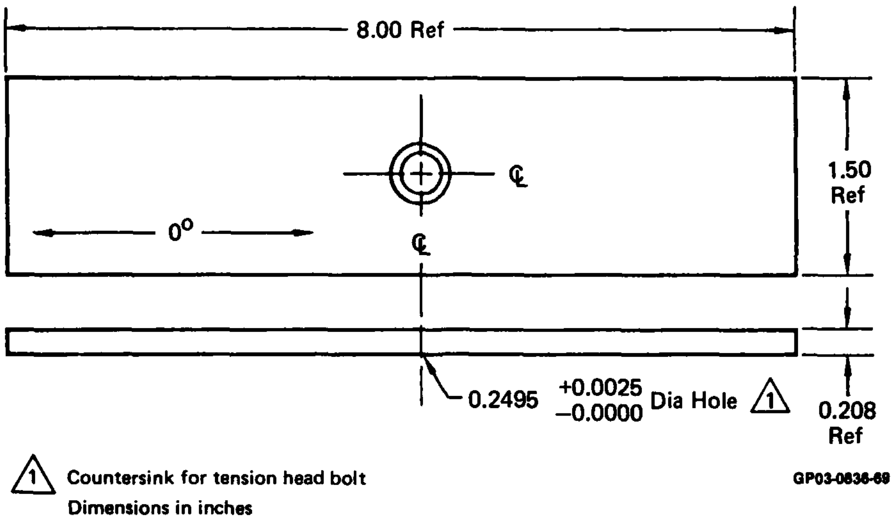


Figure 49. Test Specimen - Unloaded Hole, Fatigue Test (UHFT)

Hole Condition	Average Cycles to Failure
Baseline	3577 (1.00)
Excessive Heat	4383 (1.22) ⚠1
Delaminations - Interply	3013 (0.84) ⚠1
Hole Surface Finish > 250 RHR	3313 (0.92) ⚠1
Maximum/Minimum Strain ±4950 μin./in., Fastener Temperature < 100°F	

⚠1 Compared to baseline

GP03-0836-50

Figure 50. Fatigue Test Data

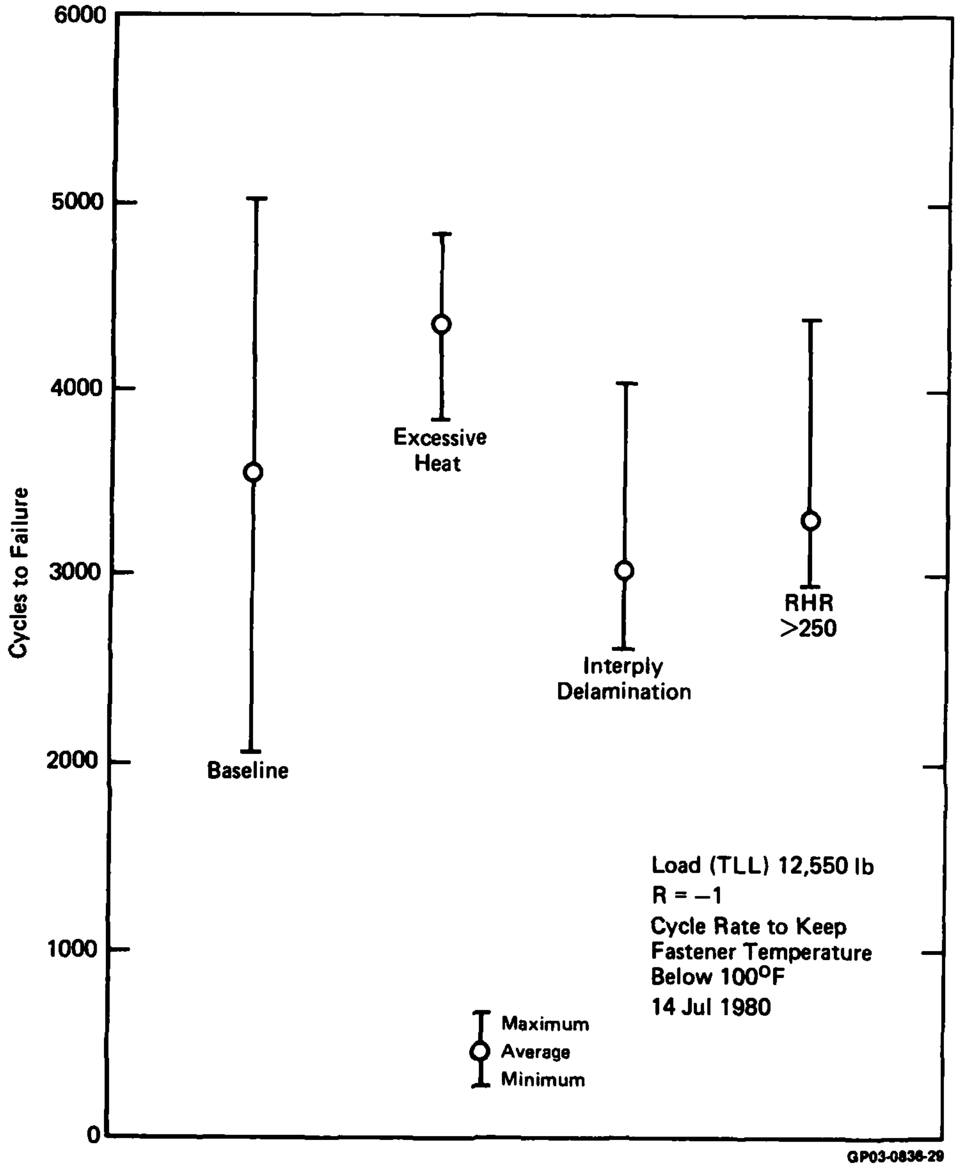


Figure 51. Fatigue Test Data

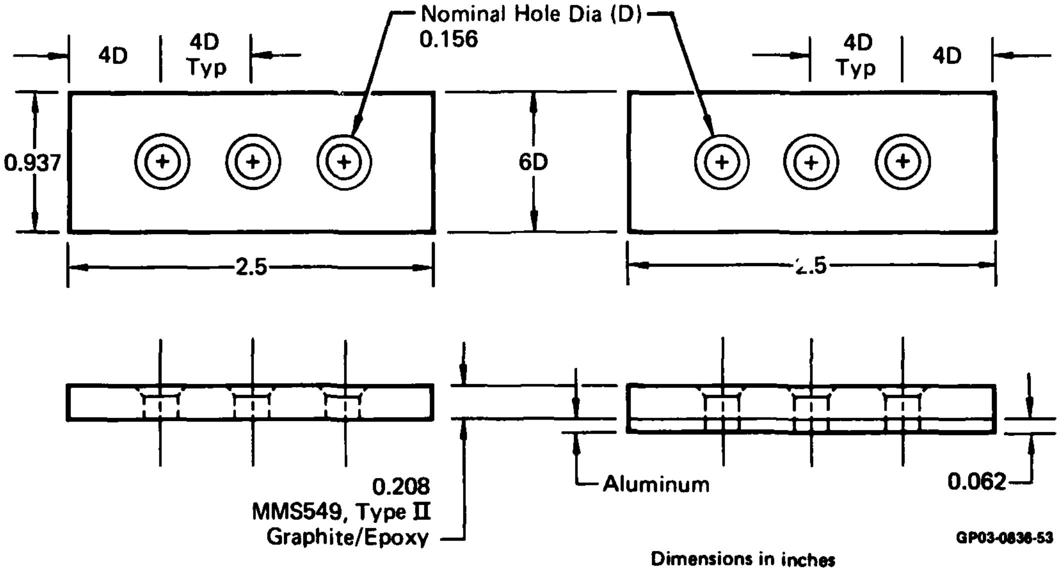


Figure 52. Fastener Installation Specimens

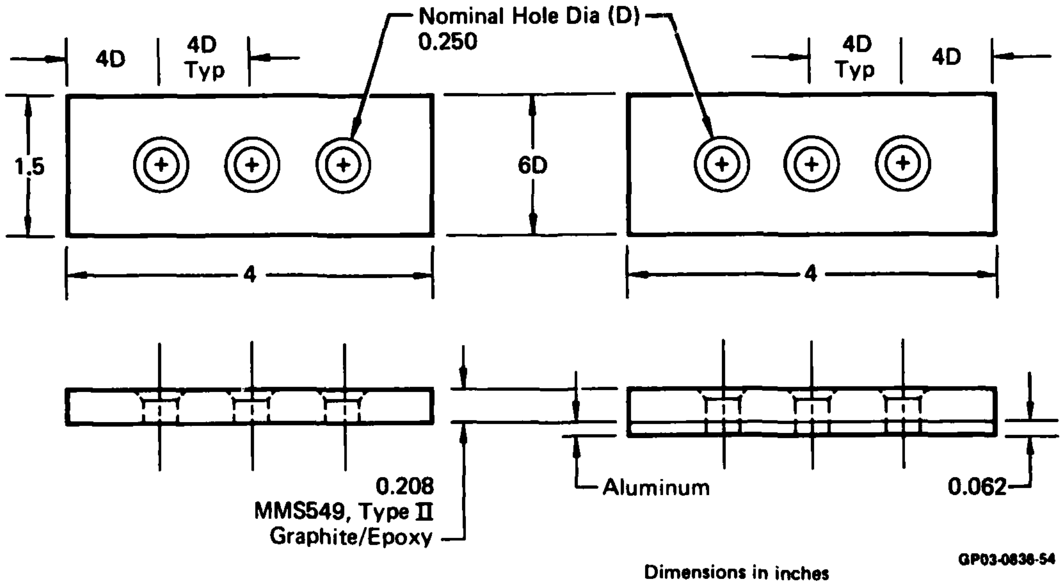


Figure 53. Fastener Installation Specimens

FASTENER NAME	SPECIMEN NO.	GRIP LENGTH		HOLE SIZE		TITANIUM BACK-UP		GRIP LENGTH ALUMINUM SPACER	WASHER	GANG CHANNEL	NUT	COLLAR
		MAX.	MIN.	MAX.	MIN.	.015	.030					
RIVET PIN-THREADED (5/32 DIA.)	1		X		X							X
	2		X		X				X			X
	3	X			X			X				X
	4	X			X			X	X			X
	5		X	X								X
	6		X	X					X			X
	7	X		X				X				X
	8	X		X				X	X			X
SOLID RIVET (5/32 DIA.)	9		X		X				X			
	10	X		X				X	X			
	11		X	X					X			
	12	X		X				X	X			
BLIND RIVET (5/32 DIA.)	13		X		X	X		X				
	14		X		X		X	X				
	15	X			X	X		X				
	16	X			X		X	X				
	17		X	X		X		X				
	18		X	X			X	X				
	19	X		X		X		X				
	20	X		X			X	X				
TENSION FLUSH HEAD BOLT HI-TORQUE RECESS (1/4 DIA.)	21		X						X		X	
	22		X							X		
	23	X							X		X	
	24	X								X		
LOCK BOLT-PULL TYPE (1/4 DIA.)	25		X					X				X
	26		X					X	X			X
	27	X						X				X
	28	X						X	X			X
BOLT, BLIND-FLUSH HEAD, (1/4" DIA.)	29		X					X				
	30	X						X				

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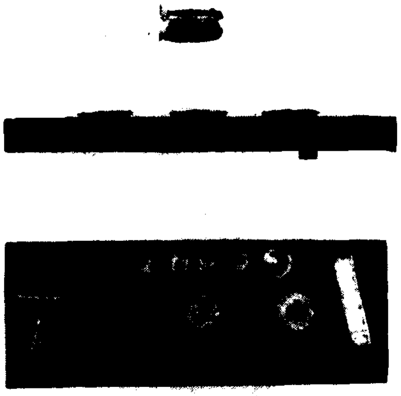
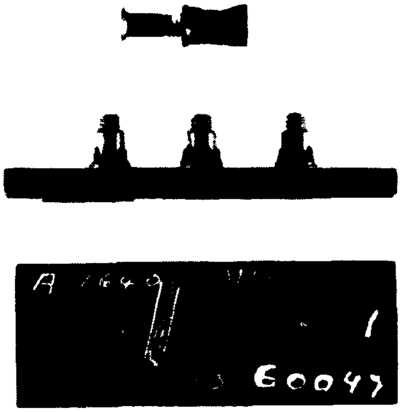
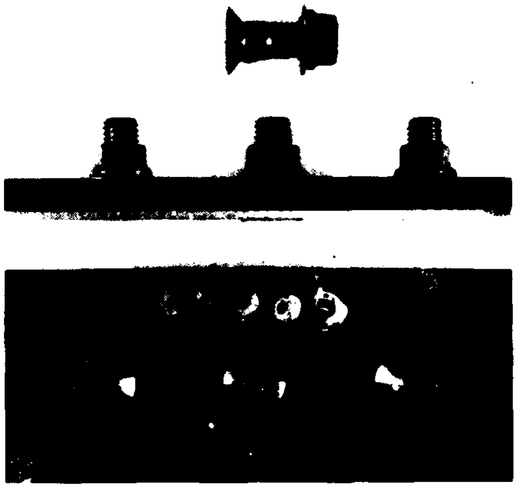
Figure 54. Fastener Installation Specimen Combinations



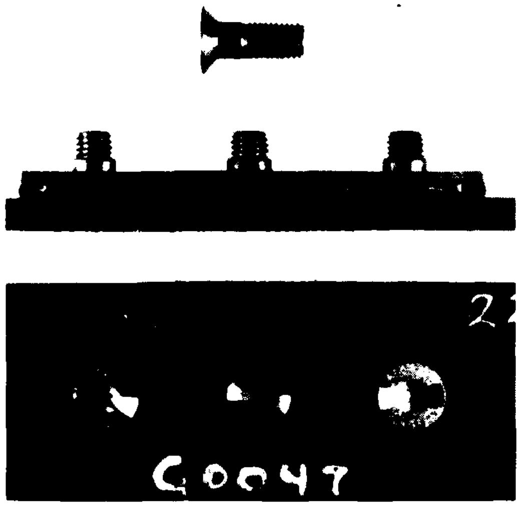
Solid Rivet - 5/32 in. Diameter



Rivet Pin - Threaded - 5/32 in. Diameter



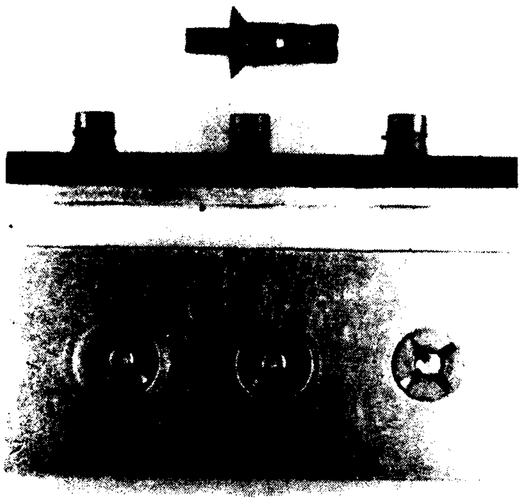
Tension Flush-Head
Bolt with Nut - 1/4 in. Diameter



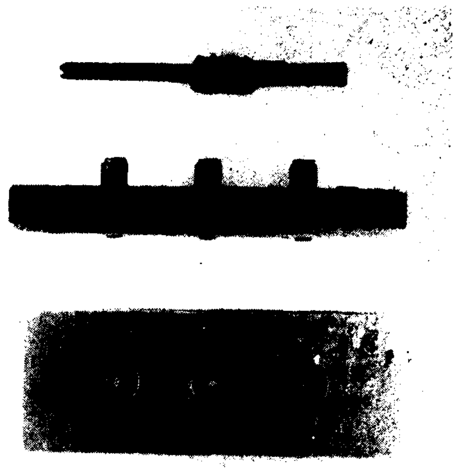
Tension Flush-Head Bolt with
Gang Channel - 1/4 in. Diameter

GP03-0836-31

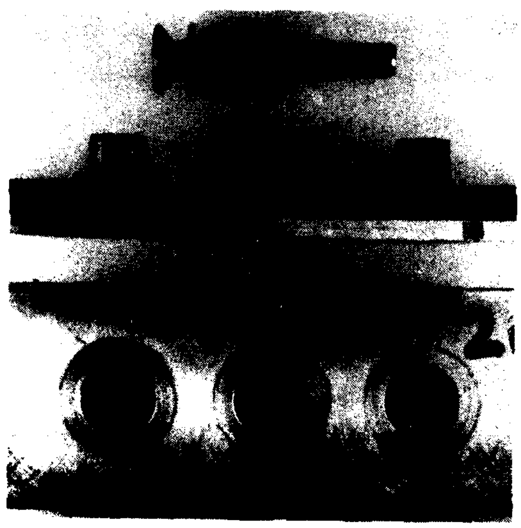
Figure 55. Fastener Installation Specimens



Bolt, Blind - Flush Head
1/4 in. Diameter



Rivet, Blind - Flush Head
5/32 in. Diameter



Lock Bolt - Pull Type
1/4 in. Diameter

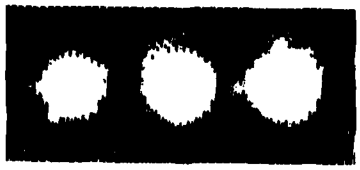
GP03-0836-32

Figure 56. Fastener Installation Specimens

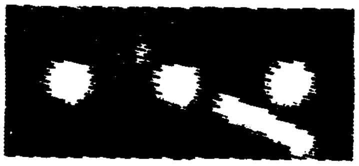
Ultrasonic C-scan inspections were performed using a reflector plate technique. A conventional reflector plate was used for the laminate specimens without metal backing. For the specimens with a metal plate or shim on one side, the composite-metal interface was used as the reflector. The specimens with metal on both sides were not inspectable due to multiple reflections of sound within the metal. In addition to the reflector plate inspections, various contact pulse-echo and through transmission inspection techniques were evaluated, however, these were not able to provide additional defect information about the specimens.

The ultrasonic C-scans revealed flaws in only 4 specimens. The C-scans of the remaining specimens revealed no damage. Pin-threaded rivet specimen number 4 gave indications of damage in each of the three holes as shown in Figure 57, with most damage being shown to one side of the center hole. Another pin-threaded rivet specimen, number 5, shows a small damage area which appears to be separated from the center hole by approximately 0.1 inch as shown in Figure 57. Figure 57 also shows some damage associated with blind-flush headed bolts; in each of the holes in specimen number 30, and somewhat more damage around the hole in specimen number 29 nearest the lead tab reference marker (identified by "#").

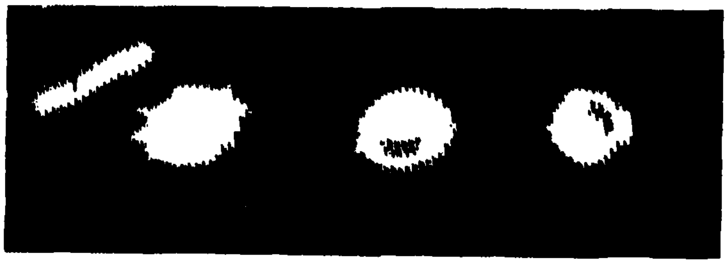
3.5.2 Sectioning Tests - Visual examination of the fastener installation specimens, in conjunction with an examination of the ultrasonic "C" scans discussed previously, was used to select 15 typical fastener areas for cross-sectioning. Figures 58 through 73 are resultant photomicrographs of the areas sectioned. Only the solid rivet conditions shown in Figure 63 and the flush head blind bolt conditions of Figure 73 indicate any fastener installation damage to the laminate. Some typical and acceptable hole preparation imperfections are evident on many of the hole walls at the 50X magnification used for making the photomicrographs. The "extra" material ply noted between the Gr/Ep laminate and the titanium back-up used with the blind rivets of specimen numbers 13 through 20, Figures 64 through 67, is an adhesive used to bond the titanium strip in place during hole preparation and fastener installation operations.



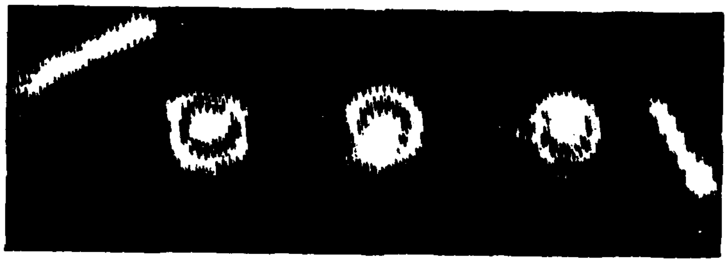
Specimen No. 4



Specimen No. 5



Specimen No. 29



Specimen No. 30 GP03-0836-40

Figure 57. Fastener Installation Specimen "C" Scans

Specimen No. 4 (5½X Before Printing) Specimen No. 5 (5½X Before Printing)

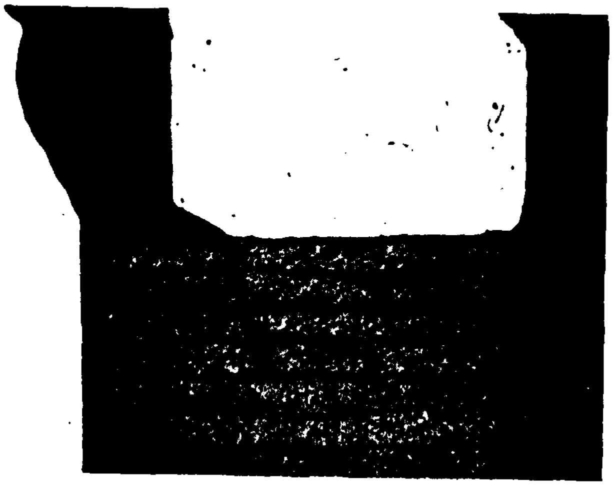
GP03-0836-43

Figure 58. Rivet Pin, Threaded

Specimen No. 4 (50X Before Printing) Specimen No. 5 (50X Before Printing)

GP03-0836-33

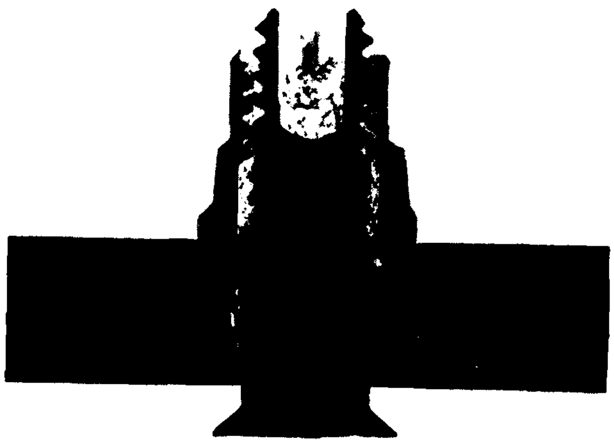
Figure 59. Rivet Pin, Threaded



Specimen No. 7 (50X Before Printing)

GP03-0836-41

Figure 60. Rivet Pin, Threaded



Specimen No. 9 (5½X Before Printing)

GP03-0836-42

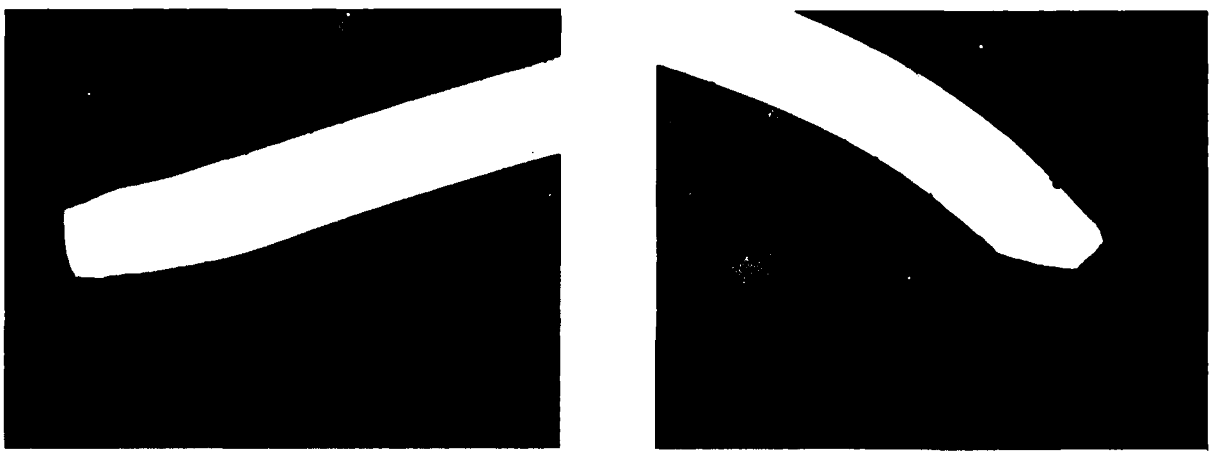
Figure 61. Rivet Pin, Threaded

Specimen No. 11 (5½X Before Printing)

Specimen No. 12 (5½X Before Printing)

GP03-0836-49

Figure 62. Rivet, Solid

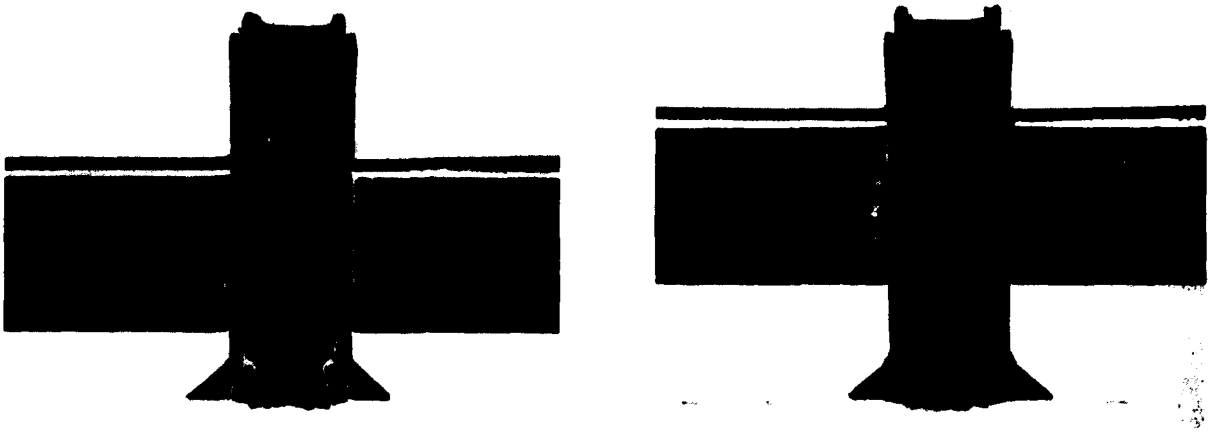


Specimen No. 11 (50X Before Printing)

Specimen No. 12 (50X Before Printing)

Figure 63. Rivet, Solid

GP03-0836-34



Specimen No. 13 (5½X Before Printing)

Specimen No. 15 (5½X Before Printing)

GP03-0636-48

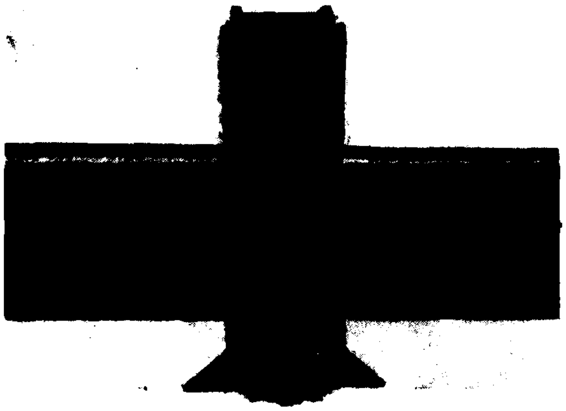
Figure 64. Rivet, Blind

Specimen No. 13 (50X Before Printing)

Specimen No. 15 (50X Before Printing)

GP03-0636-35

Figure 65. Rivet, Blind

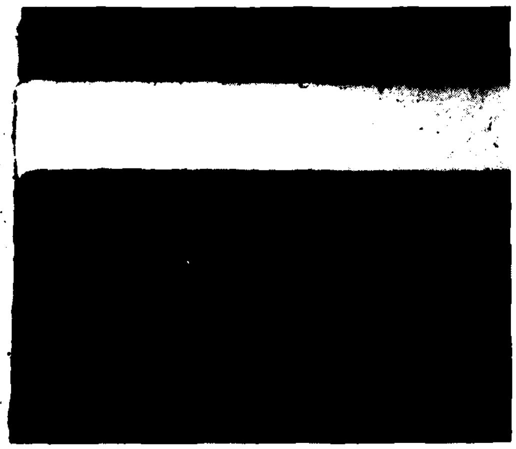


Specimen No. 17 (5½X Before Printing)

Specimen No. 19 (5½X Before Printing)

GP03-0836-47

Figure 66. Rivet, Blind

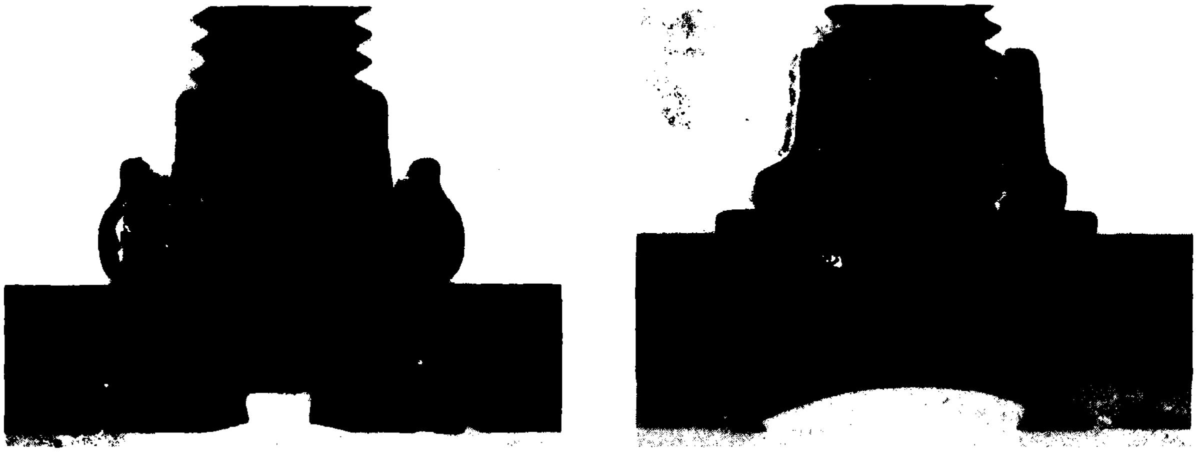


Specimen No. 17 (50X Before Printing)

Specimen No. 19 (50X Before Printing)

GP03-0836-36

Figure 67. Rivet, Blind



Specimen No. 22 (5½X Before Printing)

Specimen No. 23 (5½X Before Printing)

GP03-0836-46

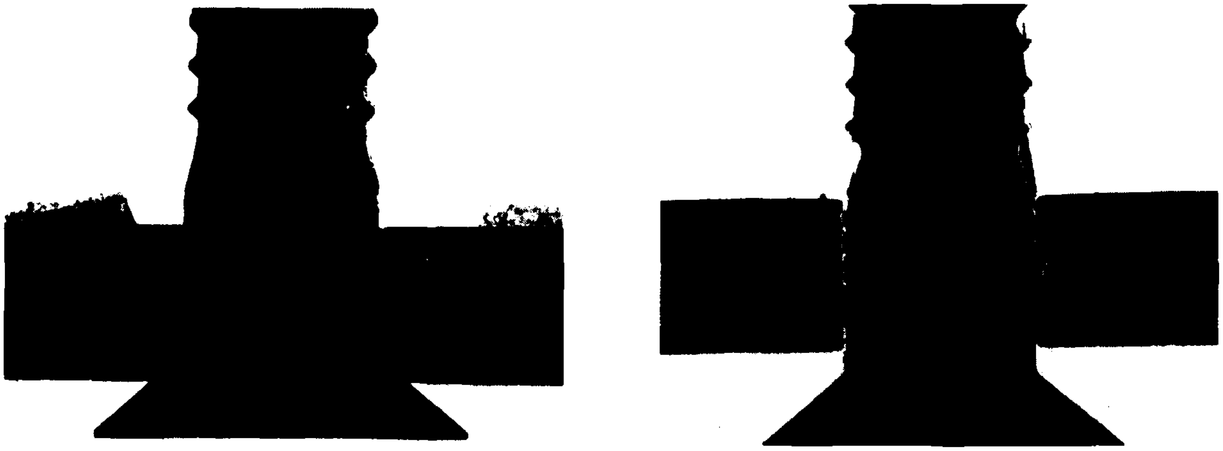
Figure 68. Flush Head Bolt

Specimen No. 22 (50X Before Printing)

Specimen No. 23 (50X Before Printing)

GP03-0836-37

Figure 69. Flush Head Bolt



Specimen No. 25 (5½X Before Printing) Specimen No. 27 (5½X Before Printing)

GP03-0836-45

Figure 70. Lock Bolt, Pull Type

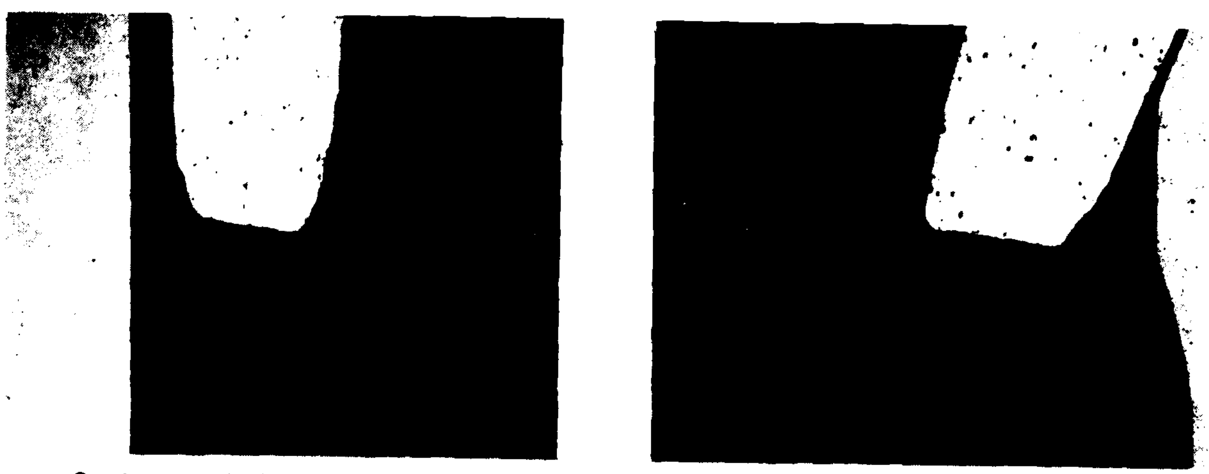
Specimen No. 25 (50X Before Printing) Specimen No. 27 (50X Before Printing)

GP03-0836-38

Figure 71. Lock Bolt, Pull Type

Specimen No. 29 (5½X Before Printing) Specimen No. 30 (5½X Before Printing)

Figure 72. Blind Bolt, Flush Head GP03-0836-44



Specimen No. 29 (50X Before Printing) Specimen No. 30 (50X Before Printing)

Figure 73. Blind Bolt, Flush Head GP03-0836-39

4.0 CONCLUSIONS AND RECOMMENDATIONS

o The dry, room temperature static and fatigue test results of this program indicate that overheating of holes, splintering, interply delaminations, and rough hole surfaces can be tolerated in Gr/Ep laminates. There is no appreciable degradation in strength as long as the fastener is present to fill the flawed hole. However, further evaluation of effects of fastener fit (hole tolerances) on laminate strength under compression loading are required to permit any relaxation of current acceptance requirements.

o Wet static tests at 250°F also indicated that these hole anomalies can be tolerated if the hole is filled.

o For unfilled holes, dry room temperature compressive strength is degraded by interply delaminations and wet 250°F compressive strength is degraded by overheating.

o Fastener installation tests demonstrated that solid rivets and flush head blind bolts should not be installed in Gr/Ep since damage is likely.

o Threaded rivet pins, blind rivets, and pull-type lock bolts can be installed without damage to the laminate. This may allow less costly fasteners to be used and also increases the variety of fasteners that may be used to satisfy a particular joint configuration. These fasteners are candidates for further performance evaluation to determine their suitability for aircraft use.

5.0 APPENDIX

DRY STATIC TEST DATA

Hole Condition	Unloaded Hole		Loaded Hole	
	Strain (Tensile) μ in/in	Strain * (Compressive) μ in/in	Strain (Tensile) μ in/in	Bearing Stress ⚠1 (Tensile) ksi
Baseline	5890	6440	3085	160
	5610	6860	3355	158
	5725	6510	3230	156
Excessive Heat	5660	6840	3510	165
	5555	7055	3360	169
	5245	7070	3190	162
Delaminations: Some Splintering	5475	6970	3310	163
	5610	7045	3215	165
	5515	7250	3140	156
Delaminations: Much Splintering	5655	6710	3150	162
	5980	7120	3035	153
	5610	7240	3220	163
Delaminations: Interply	5865	4940	3035	144
	5890	5990	2990	154
	5820	5430	3000	156
Hole Surface Finish > 125 RHR	5820	6210	3125	154
	5705	6385	3220	160
	5450	6470	3120	153
Hole Surface Finish > 250 RHR	5475	6120	3230	162
	5450	6340	3290	160
	5705	6805	3275	163

* No fastener in hole

⚠1 $F_x^{bru} = \frac{P^u}{(d)(t)}$

where: P^u = ultimate load
d = fastener diameter
t = specimen thickness

Test Temperature 75°F

WET STATIC TEST DATA

Hole Condition	Unloaded Hole	Loaded Hole	
	Strain * (Compressive) μ in/in	Strain (Tensile) μ in/in	Bearing Stress △1 (Tensile) ksi
Baseline	4480 5235 5040	2540 2375 2390	121 119 117
Excessive Heat	3740 4145 2830	2365 2250 2420	116 108 115
Delaminations: Interply	2845# 4840 4250	2515 2365 2485	113 107 109
Hole Surface Finish > 250 RHR	5630 5245 4946	2715 2735 2590	114 116 116

* No fastener in hole

\# Gage slipped

1% moisture, 250°F test temperature

△1 $F_x^{bru} = \frac{pu}{(d)\ (t)}$

where: p^u = ultimate load
d = fastener diameter
t = specimen thickness

FATIGUE TEST DATA

(DRY SPECIMENS)

HOLE CONDITION	CYCLES TO FAILURE
BASE LINE	3630 5060 2040
EXCESSIVE HEAT	4860 3850 4440
DELAMINATIONS - INTERPLY	4040 2620 2380
HOLE SURFACE FINISH > 250 RHR	2580 4400 2960
MAXIMUM/MINIMUM STRAIN $\pm$ 4950 μ IN./IN FASTENER TEMPERATURE $<$ 100°F TEST TEMPERATURE 75°F	

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